DWLBC REPORT

Uley Basin Groundwater Modelling Project

Volume 1: Project Overview and Conceptual Model Development

2006/01

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

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Nikki Harrington, Scott Evans and Dragana Zulfic

Knowledge and Information Division
Department of Water, Land and Biodiversity Conservation

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Department of Water, Land and Biodiversity Conservation

25 Grenfell Street, Adelaide

GPO Box 2834, Adelaide SA 5001

Telephone	National	(08) 8463 6946
	International	+61 8 8463 6946
Fax	National	(08) 8463 6999
	International	+61 8 8463 6999
Website	www.dwlbc.sa.gov.au	

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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

ACKNOWLEDGEMENTS

Thanks to SA Water and the Eyre Peninsula Natural Resources Management Board for initiating the project and providing financial support. Many thanks to Glenn Harrington (DWLBC) and Nara Somartne (SA Water) for their input to discussions about the conceptual model.

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EXECUTIVE SUMMARY

BACKGROUND AND OBJECTIVES

The Uley Basin forms part of the Southern Basins Prescribed Wells Area (PWA). The basin contains the Quaternary Bridgewater Formation Limestone and Tertiary Sands aquifers. Where the former is saturated, the Uley Wanilla, Uley East and Uley South groundwater lenses occur. These fresh groundwater lenses are at risk of degradation of quantity and quality if over-exploited. Groundwater in the basin is fully allocated, primarily meeting the demand of the reticulated water supply for Eyre Peninsula. The Uley South lens alone provides more than 70% of the total reticulated water use for Eyre Peninsula.

In response to concerns regarding (i) the high dependency on these groundwater resources, (ii) the understanding that they are currently being utilised close to or at their available yield, (iii) the effects on long-term sustainable yields of factors such as climatic variability and climate change (global warming), and (iv) the fact that recharge rates and hence sustainable yields of these groundwater lenses are estimated with a moderate degree of certainty at this stage, the Uley Basin Groundwater Modelling Project was initiated by SA Water and the Eyre Peninsula Natural Resources Management Board in September 2005.

The objectives of this project are to develop a numerical groundwater model to better determine:

- An improved estimate of sustainable yields from the Uley Basin aquifers.
- A predicted response of the aquifer system to potential groundwater use scenarios.
- The long-term risks to the aquifer system associated with inadequate management.
- A predicted response of the aquifer system to climatic variability, risk of over extraction and specifically the impact on the available yield.

The outcomes of the project will be:

- A more robust understanding of the groundwater system upon which to base resource management decisions.
- A groundwater flow model that will incorporate our understanding of the groundwater flow system to date and act as a useful tool with which to assess management scenarios.
- A good understanding of the critical knowledge gaps and subsequently the further work required to ensure that model predictions of aquifer response to management scenarios are as accurate as possible.

Although the main focus of the project is on determining a sustainable groundwater extraction regime for the Uley South groundwater lens, the study involves the development of a conceptual and numerical model for the entire Uley Basin, including the Uley Wanilla, Uley East and Uley South lenses. In this report, all existing information on the Uley Basin has been reviewed and used to develop a conceptual model for groundwater flow and solute transport within the system.

Following this, a steady state numerical model will be developed and calibrated against pre-extraction (pre-1949) groundwater levels and salinities and provide the basis for development of a transient model that incorporates groundwater extraction, commencing in the Uley Wanilla lens in 1949 and Uley South lens in 1976. The transient model will also be calibrated against observed groundwater levels and salinities before being used to test a variety of scenarios, including:

- Different groundwater extraction regimes to obtain information on the sustainable yields of the groundwater lenses.
- A shift in climate from winter dominated rainfall towards more summer rainfall, and an overall reduction in rainfall, both leading to reduced recharge.
- Sea level rise.

MAJOR CONCLUSIONS FROM THE CONCEPTUAL MODELLING PROCESS

A great deal of information already exists from previous studies on the hydrogeology of the Uley Basin and has been used in this report in the development of a conceptual model for groundwater flow and solute transport within the two main aquifer systems in the basin, the Quaternary aquifer groundwater lenses and the Tertiary Sand aquifer. This is summarised on a series of conceptual model (cross-sectional and spatial) and water balance diagrams. Some of the major conclusions from the conceptual modelling exercise are:

- All Quaternary aquifer groundwaters have residence times less than 30 yrs.
- Tertiary aquifer groundwaters generally have residence times greater than 35 yrs. One estimate of groundwater residence time in the Tertiary Sand below Big Swamp is 3000–6500 yrs.
- Similar chemical histories suggest that groundwater in the Tertiary Sand aquifer has been recharged through the Quaternary aquifer.
- The Quaternary aquifer is dynamic, responding rapidly to seasonal and longer term changes in rainfall.
- The major control on groundwater salinity in the Uley Basin is likely to be evapotranspiration of rainfall recharge, with (almost) all incident rainfall being evapotranspired in summer, leaving dissolved salts behind at the ground surface or in the thin soils of the basin to be dissolved and carried into the Quaternary aquifer by winter recharge.
- If this model of groundwater salinisation is accurate, a climate shift from winter dominated rainfall towards more summer rainfall with less falling in winter, under the same evapotranspiration conditions, is likely to have the greatest impact on Quaternary aquifer groundwater salinities.
- The chloride mass balance and water balance methods provide good spatially averaged estimates of average annual rainfall recharge to the groundwater lenses, whilst CFC data provides good point estimates of average annual recharge.
- The limiting winter rainfall method of Barnett (1978) may be the most useful in estimating temporal distributions of rainfall recharge across the three groundwater lenses, for use in the numerical modelling exercise. This should be guided by the average annual recharge estimates derived by Evans (1997) using a variety of methods.

- Leakage from Big Swamp controls the groundwater salinity along the eastern portion of the Uley East lens and also influences groundwater salinities in the Tertiary Sand aquifer below this lens.
- Direct recharge to the Tertiary Sand aquifer occurs through the unsaturated Quaternary limestone aquifer in the central portion of the study area (between the Quaternary lenses).
- Groundwater residence times are greater in the Uley Wanilla lens (11–30 yrs) than in the other two Quaternary aquifer lenses (8–16 yrs). This is possibly an effect of high levels of groundwater extraction from this lens and the resulting disruption to the groundwater flow system.
- Mass balance calculations suggest that downward leakage to the Tertiary Sand aquifer is greater from the Uley East lens than from the other two lenses (App. C). Such leakage may occur anywhere along the lenses as well as from their southern extremeties.
- Upward leakage from the Tertiary Sand to the Uley South lens, with a magnitude of the order of 14 mm/y, is possible in the zone to the south west of Cross Section BB', but is a relatively small component of the water budget for that lens.
- A simple mass balance model can be used to reasonably match trends in groundwater hydrographs for the Quaternary aquifer lenses, providing overall confidence in the conceptual models of the lenses and some quick and easy preliminary information on likely impacts on groundwater levels of different groundwater extraction scenarios. This can probably also be applied to investigate various climate change scenarios.

Limitations of the conceptual model and their likely impacts on the outcomes of the numerical modelling exercise were summarised in Chapter 5.

Due to the occasionally large gaps in quantitative data in some areas of the conceptual model and the problem that this implies for calibration of the numerical model, it is recommended that some of the semi-quantitative and qualitative information presented in this report be used in calibration and assessment of the final model along with the usual method of hydraulic head matching. Examples include qualitative information on groundwater flow and areas of inter-aquifer leakage, semi-quantitative information on likely ranges of groundwater residence times, flow rates and total fluxes. It is also recommended that the numerical modelling process be used to determine the gaps in the conceptual model that are critical to the outcomes of the project.

1. INTRODUCTION

1.1 BACKGROUND

The Uley Basin forms part of the Southern Basins Prescribed Wells Area (PWA). The basin contains the Quaternary Bridgewater Formation Limestone and Tertiary Sands aquifers. Where the former is saturated, the Uley Wanilla, Uley East and Uley South groundwater lenses occur (see Map 1)[1]. These fresh groundwater lenses are at risk of degradation of quantity and quality if over-exploited. Groundwater in the basin is fully allocated, primarily meeting the demand of the reticulated water supply for Eyre Peninsula. The Uley South lens alone provides more than 70% of the total reticulated water use for Eyre Peninsula.

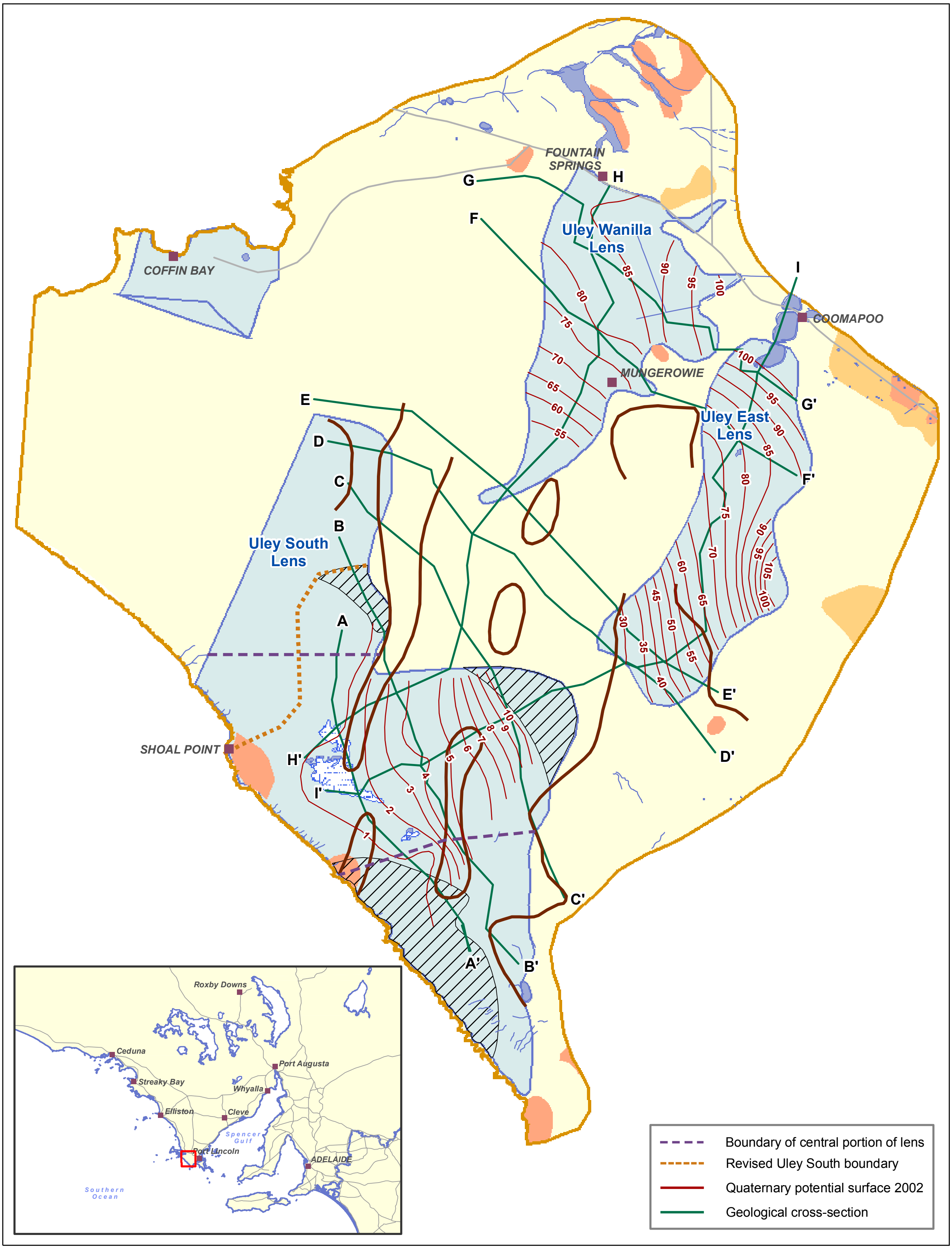
Given the high dependency on these groundwater resources and the understanding that they are currently being utilised close to or at their available yield, there is concern about the effects on long-term sustainable yields of factors such as climatic variability (local rainfall patterns – frequency and intensity dictate the effectiveness of annual recharge) and climate change (global warming, with the prediction of less winter rainfall and increased summer rainstorms, which may further affect recharge). A particular issue is that recharge rates and hence sustainable yields of these groundwater lenses are estimated with a moderate degree of certainty at this stage and any additional development within Eyre Peninsula could increase water supply pressure on the lenses, particularly the Uley South lens. In response to the above concerns, the Uley Basin Groundwater Modelling Project was initiated by SA Water and the Eyre Peninsula Natural Resources Management Board in September 2005.

1.2 PREVIOUS WORK IN THE ULEY BASIN

A number of workers have carried out investigations into the hydrogeology of the Uley Basin, providing a starting point for this project. However, most of these investigations focused on the Quaternary aquifer or the hydrogeology and safe yield of the Uley South lens area. The result is that, with the exception of the Uley South area, the geology below the Quaternary aquifer is generally poorly understood. The geology of the Southern Basins was described by Segnit (1942), Johns (1961) and Wilson (1991). Shepherd (1963) described the hydrogeological information obtained from drilling 154 boreholes in the Kellidie Bay – Sleaford Mere area between 1959–63. Painter (1969) carried out an evaluation of the aquifers in the Uley South area, through geological mapping and pump tests. Morton and Steel (1970) summarised the work of Shepherd (1963) and described the results of three additional pumping tests in the Uley South Basin, including estimates of available yields.

Using a storage change / Darcy's Law method and the results of Shepherd (1963), Painter (1969) and Morton and Steel (1970), Selby (1974) estimated that the annual outflow from the Uley South basin between the years of 1962–71 was ~50% of rainfall. Through drilling and testing of a new exploratory well, Barnett (1978) confirmed a relationship between high transmissivities and low hydraulic gradients in the Uley South area. Barnett (1978) also

1. The use of the term "lenses" in the context of this region refers to where the Quaternary Bridgewater Formation limestone is saturated. Saturation is typically controlled by geologic structure. This is different from the usual definition of a groundwater lens, which is a saturated area defined by a certain groundwater salinity contour.



Map 1. Site map showing locations of Quaternary groundwater lenses, geological cross-sections (Appendix A), surface geology and areas where Tertiary clay is absent

Locality
Drainage
Road
Waterbody
Swamp
Uley Basin
Quaternary groundwater lens

Tertiary sand extent
Tertiary clay absent

Geology

Quaternary sediment
Tertiary sediment
Basement outcrop

N

0 1.25 2.5 5 km

Map Production: Resource Information Group
Department of Water, Land and Biodiversity Conservation

Map Projection: MGA Zone 53
Map Datum: GDA94.

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calculated a water balance for the Uley South lens based on the information available at the time. An estimate of a base winter rainfall, below which no recharge occurs, was also made based on a relationship between water table fluctuation and rainfall. This could then be used to estimate recharge rates for the lens. This method is discussed in more detail in subsequent sections of this report.

Evans (1997) estimated recharge to the Uley Wanilla, Uley East and Uley South lenses using a variety of methods, ranging from Darcy's Law calculations to measurement of environmental tracers such as CFCs. The results of this study are discussed in detail throughout this report.

Martin and Clarke (2000) carried out a review of the relationship between rainfall and groundwater extraction and groundwater levels in the Uley Basin, providing recommendations for (i) additional monitoring of groundwater levels and quality, and (ii) numerical modelling of the groundwater resource to aid management. James-Smith and Brown (2002) subsequently constructed a single layer numerical groundwater flow model of the Uley South groundwater lens. Using two recharge zones, with recharge being constant from year to year, but concentrated in the winter period (April–October), James-Smith and Brown (2002) were able to reasonably reproduce the general groundwater hydrograph trends observed during the pre-pumping (steady-state) and pumping (transient) periods. Due to the difficulty in characterising recharge over time, and the resulting application of a constant recharge regime, the model was unable to reproduce some of the major peaks and troughs observed in the groundwater hydrographs that are caused by large fluctuations in annual rainfall. Another major limitation of this model was the imposition of rigid boundary conditions around the groundwater lens, which artificially controlled the dynamics of the lens.

Clarke et al. (2003) carried out evaluation and augmentation/rehabilitation of the existing groundwater monitoring network in the Uley South lens, and a geophysical survey to determine the position of the seawater interface.

2. OBJECTIVES AND OUTCOMES

The objectives of the current project are to develop a numerical groundwater model to better determine:

- The estimate of sustainable yields from the Uley Basin aquifers.
- A predicted response of the aquifer system to potential groundwater use scenarios.
- The long-term risks to the aquifer system associated with inadequate management.
- A predicted response of the aquifer system to climatic variability, risk of over extraction and specifically the impact on the available yield.

The outcomes of the project will be:

- A more robust understanding of the groundwater system upon which to base resource management decisions.
- A groundwater flow model that will incorporate our understanding of the groundwater flow system to date and act as a useful tool with which to assess management scenarios.
- A good understanding of the critical knowledge gaps and subsequently the further work required to ensure that model predictions of aquifer response to management scenarios are as accurate as possible.

3. METHODOLOGY

Although the main focus of the project is on determining a sustainable groundwater extraction regime for the Uley South groundwater lens, the study involves the development of a conceptual and numerical model for the entire Uley Basin, including the Uley Wanilla, Uley East and Uley South lenses. In this report, all existing information on the Uley Basin has been reviewed and used to develop a conceptual model for groundwater flow and solute transport within the system (Ch. 4). This includes information on:

- Hydrostratigraphy, particularly in relation to its effect on groundwater flow and boundary conditions.
- Groundwater inflows to and outflows from the Tertiary Sand aquifer and Quaternary aquifer groundwater lenses, including rainfall recharge, surface water and groundwater inflows and groundwater extraction.
- Aquifer and aquitard properties from pumping tests (quantitative) and indirect observations (qualitative).
- Historical and current groundwater levels and inferred flow rates and directions.
- Information from groundwater chemistry and isotopic signatures on groundwater recharge and flow, and sources of salinity.

A preliminary assessment of the conceptual model is carried out through the development and evaluation of a series of water and salt balances (Chs 6–7).

Details of the construction of a preliminary steady state numerical groundwater flow model will be included in a subsequent report, including the collation and validation of hydrostratigraphy information from the State database, SAGeodata, development of the model grid and boundary conditions and allocation of layer properties.

The steady state numerical model will be calibrated against pre-extraction (pre-1949) groundwater levels and salinities and provide the basis for development of a transient model that incorporates groundwater extraction, commencing in the Uley Wanilla lens in 1949 and Uley South lens in 1976. The transient model will also be calibrated against observed groundwater levels and salinities before being used to test a variety of scenarios, including:

- Different groundwater extraction regimes to obtain information on the sustainable yields of the groundwater lenses.
- A shift in climate from winter dominated rainfall towards more summer rainfall, and an overall reduction in rainfall, both leading to reduced recharge.
- Sea level rise.

Throughout the modelling process, limitations in the conceptual model will be identified and assessed in terms of their likely impact on the overall outcomes of the project. Recommendations will be made for further work to fill in any critical gaps and improve confidence in the outcomes from the numerical model.

4. REVIEW OF EXISTING SITE INFORMATION, GROUNDWATER CHEMISTRY AND ISOTOPE DATA: CONCEPTUAL MODEL DEVELOPMENT

A review of existing information on the groundwater flow systems of the Uley Basin is provided below, with the discussion being divided into hydrogeological units. The geology of the Southern Basins has been described extensively by Segnit (1942), Johns (1961) and Wilson (1991). However, the geological descriptions of the Uley Basin included in the following are summarised from reviews of these in Morton and Steel (1970) and Evans (1997). Appendix A is reproduced from Evans (1997) and includes geological cross sections through the Uley Basin that will be referred to below (see Map 1 for locations of cross sections).

As part of the present project, a review of the groundwater chemistry and isotope data collected by Evans (1997) was also carried out. The objective of the study of Evans (1997) was to investigate mechanisms and rates of recharge to the Quaternary groundwater lenses. Here, we expand the interpretation of the data to include inferences that can be drawn about groundwater sources, outflows, flow paths and flow rates.

4.1 PHYSICAL CHARACTERISTICS OF THE ULEY BASIN

All information included in this section is summarised from Evans (1997). The study area is bounded to the east by the southerly extension of the exposed basement rock of the Lincoln Uplands, and by the lateral extent of the Quaternary Bridgewater Formation limestone aquifer to the north. Mobile dunes and partially exposed basement highs form the western boundary of the study area, and the coastline to the Southern Ocean is the southern boundary (Figs 4.1a–d).

The topography, particularly in the lens areas, is a result of ancient dune systems, with distinct dune ridges and subtle undulations defining local surface drainage systems. The Uley South area (Map 1; Fig. 4.2) is a topographically closed surface drainage basin, with a flat to undulating centre at an elevation of less than 20 m AHD. The Uley South basin is bounded to the west, north and east by topographic rises up to 140 m AHD. These are a result of the rising basement sub-structure. The basin is bounded to the south by a set of coastal cliffs that also rise to greater than 140 m AHD (Figs 4.1c, d). The Uley Wanilla and Uley East areas (Map 1) rise from 60–70 m AHD in the south to a flat to undulating plateau at approximately 100 m AHD in the north.

Most of the study area is Crown Land, set aside for the protection of the potable water resource, but the eastern portion, the Uley East lens is still privately owned and land use is primarily pastoral.

Figure 4.1a. View towards the mobile sand dunes that form the western boundary of the Uley South lens.

Figure 4.1b. Mobile sand dunes that form the western boundary of the Uley South lens.

Figure 4.1c. View towards the south-western boundary of the Uley Basin, showing the rise to the coastal cliffs at the Southern Ocean.

Figure 4.1d. Coastal cliffs at the south-western boundary of the Uley Basin.

Figure 4.2. Looking south-west across the central Uley South lens region.

Soils in the Uley Basin are typically (i) skeletal calcareous or (ii) shallow sandy and clayey loams, generally less than 30 mm thick and associated with surface limestone outcrops (Fig. 4.3). They can be up to 50 mm thick in shallow depressions. A sheet limestone sub-strata is often present, predominantly on local rises.

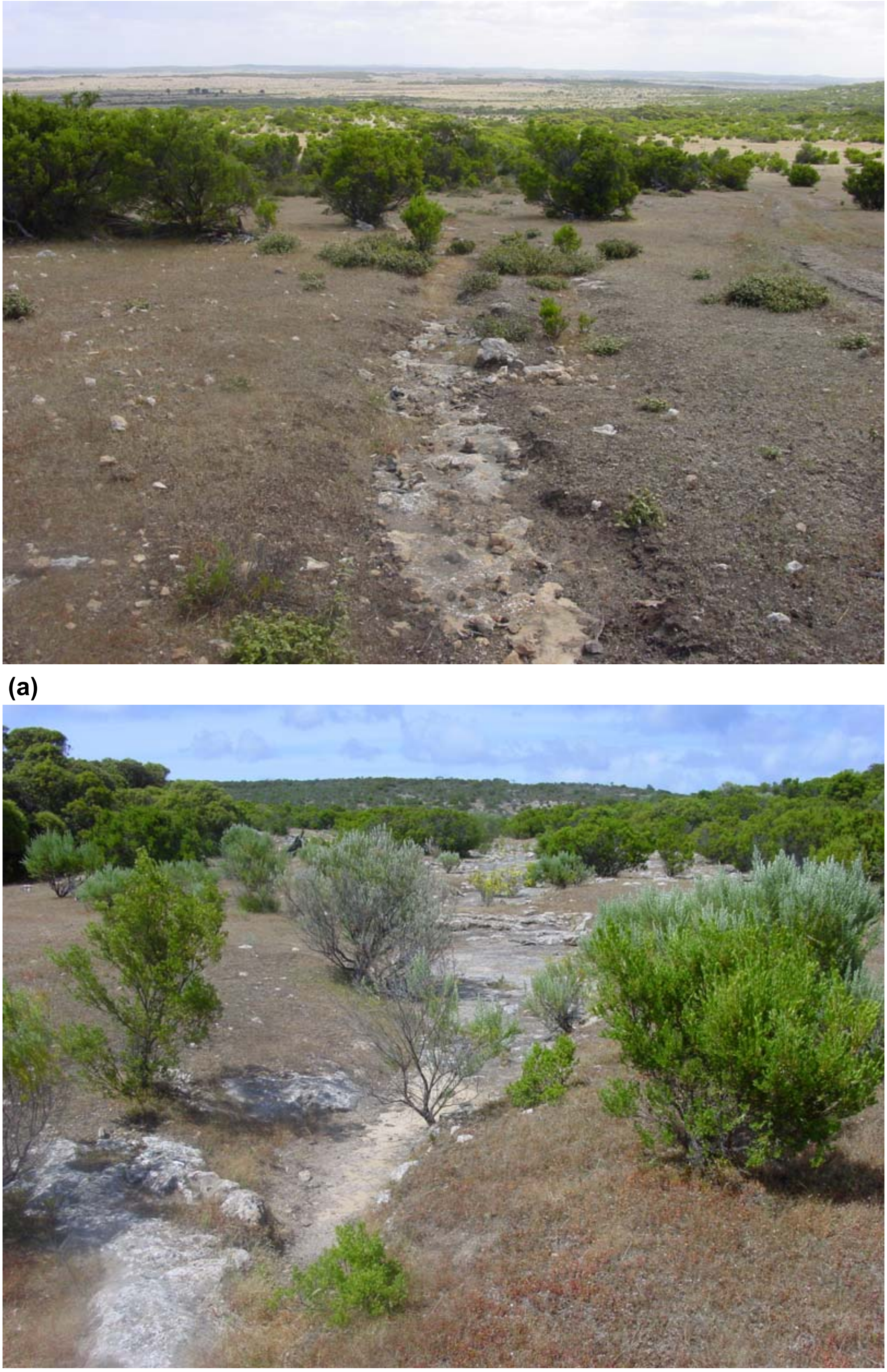
Surface watercourses are rare in the Uley Basin. Where present, they are tens to hundreds of metres long and terminate abruptly at sinkholes within surface depressions. The streams are ephemeral, occur in elongate washouts where there is no surface soil layer, and are most common on the inland slopes of the coastal cliffs in the Uley South lens area (Fig. 4.4). There are no surface water outflows from the Uley Basin, with all surface watercourses draining inward.

Big Swamp, an annual inundated surface water body located in the north eastern portion of the basin (Map 1), acts as an endpoint for surface drainage systems to the north east of the Uley Basin and consists of three sections. The northerly two sections directly overlie the Tertiary Clay and receive wet season dominated surface runoff. Water holds well in these sections and is removed by evaporation in summer. Salinity during the late stages of drying in these sections has been observed to be 10 300 mg/L, compared with 1000–5500 mg/L during the wet season.

The third, southerly section of Big Swamp fills infrequently during the wet season from the second section (~2 in every 5 yrs). This section overlies the Quaternary limestone and hence provides recharge to this aquifer during wet years, occasionally overflowing and draining south into the Uley East lens area, then west into the Uley Wanilla area approximately one year in twenty, where the surface water is believed to infiltrate the limestone. The salinity of this flooding surface water is believed to be > 1000 mg/L.

Figure 4.3a. Shallow soil overlying quaternary limestone, typical of the Uley Basin.

Figure 4.3b. Typical exposed limestone sub-strata on a basement ridge.



(a)

(b)

Figure 4.4. Exposed limestone in surface runoff channels from the coastal cliffs into the Uley South lens.

Dense stands of mallee vegetation occur above the 30 m AHD topographic contour, with isolated stands occurring below this. Large areas of the basin are densely covered with vegetation, with mallee prevalent in the Uley Wanilla and Uley East areas and some Red Gums on the northern boundary of Big Swamp (Fig. 4.5). There are some isolated areas where drooping sheoak may have been the predominant vegetation species, to the south of Big Swamp and in the southern area of the Uley Wanilla and Uley South lenses.

South Australian Swamp paperbark, dryland tea-tree and current bush dominate in the central portion of the Uley Wanilla lens. These are considered to have regenerated following a previous pastoral land use. This vegetation results in up to 90% canopy cover in some parts of the Uley Basin area.

The climate across the southern Eyre Peninsula is semi-arid to sub-humid, with a predominant cold wet season occurring between May and October and a warmer dry season from November to April. The nearest temperature measurement station was at Port Lincoln and is now at the Port Lincoln airport, and pan evaporation is measured at the Tod Reservoir. It is considered that the latter, measuring annual pan evaporation between 1130–1610 mm, may not be representative of conditions across the entire basin due to its protected location and different physiographic characteristics (Evans, 1997).

Rainfall has been measured at Big Swamp since 1897 and more recently within the Uley Wanilla and Uley South lenses. Tipping bucket pluviometers were installed in the Uley Wanilla and Uley South lenses from July, 1993–97. Measured annual rainfall is similar for the three stations, ranging between 351–925 mm (Evans, 1997). Tipping bucket pluviometers were installed at sites within the Uley South and Uley Wanilla lenses in 2002.

Figure 4.5. Vegetation of the Uley Wanilla lens area.

There have been no studies of evapotranspiration in the Uley Basin, and given the dense vegetative cover across most of the basin, evapotranspiration of rainfall is likely to be a large part of the water balance. A swampy area, ~0.85 km^2 that occurs just inland of the coastal cliffs in the Uley South lens area. Here, the depth to water can be less than 1 m and the area is known to be inundated during periods of intense rainfall. The swampy area is vegetated with cutting grass or sword sedge, with an estimated leaf area index of approximately two. Although evapotranspiration may be a significant process in this area, the area itself is relatively small in relation to the whole basin area, and the magnitude is therefore likely to be small in the context of the overall basin water balance.

4.2 GENERAL GROUNDWATER CHEMISTRY AND ISOTOPIC SIGNATURES

4.2.1 SALINITY ([Cl$^-$]) AND STABLE ISOTOPE SIGNATURES (δ^{18}O AND δ^2H)

4.2.1.1 Relationship Between TDS and [Cl$^-$]

Evans (1997) describes extensively the chemistry of groundwaters and surface waters in the Uley Basin, particularly in relation to recharge processes. All chemistry and isotope data referred to in the present report were collected by Evans (1997) and are also discussed there. Chloride concentrations ([Cl$^-$]) are used in this report as an indicator of relative salinities as, in the absence of chloride-bearing evaporite minerals, chloride is the most geochemically conservative of the major anions and can therefore be used directly to calculate concentration or evaporation factors. Figure 4.6 shows a graph of the TDS against chloride concentrations for the Quaternary and Tertiary groundwaters from the Uley Basin, with data from Evans (1997). In this case, a good linear relationships exists between TDS and [Cl$^-$] and hence, the relationship, TDS = 2.0045[Cl$^-$]+340 can be used to calculate TDS based on calculated chloride concentrations for the Quaternary aquifer (Fig. 4.6). The linear relationships are remarkably similar for the Tertiary and Quaternary groundwaters, indicating similar chemical histories and hence origins for the groundwaters in the two aquifers. This will be discussed in more detail in the next section.

4.2.1.2 Rainfall and Surface Water

The [Cl$^-$] of rainfall in the Uley Basin area should theoretically range between ~8 mg/L for the Uley Wanilla lens and 14 mg/L for the Uley South lens, based on the distance of measuring points from the ocean and the method of Hutton and Leslie (1958) (Evans, 1997). The [Cl$^-$] of surface water from Big Swamp, sampled in the early 1940s ranged between 1370–3040 mg/L. The stable isotope signature of Uley Basin rainfall, as measured by Evans (1997), generally ranged between δ^2H = -61.9 ‰; δ^{18}O = -9.24 ‰ and δ^2H = -0.4 ‰; δ^{18}O = -0.28 ‰. The stable isotope composition of surface water from Big Swamp has not been measured.

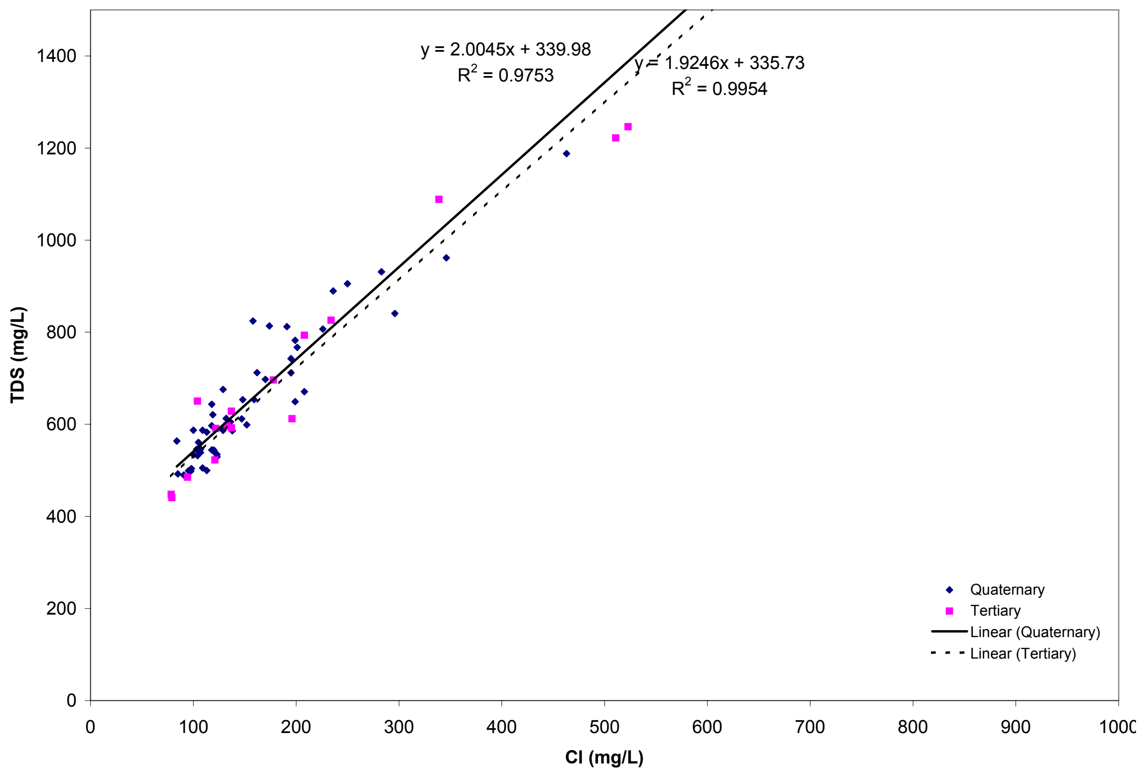


Figure 4.6. Plot of TDS/Cl vs Cl for all Quaternary and Tertiary groundwaters.

4.2.1.3 General Controls on Groundwater Salinity

[Cl⁻]s of the Quaternary aquifer groundwaters in the Uley Basin range between 84–1264 mg/L, with the majority of values being below 300 mg/L. Such generally low [Cl⁻]s suggest relatively little evapotranspiration of incident rainfall prior to recharge compared with many other areas of Australia. However, in the absence of any significant ancient salt deposits, the increase in salinity from that of incident rainfall (8–14 mg/L) to that of the Quaternary aquifer groundwater (~350 mg/L) does indicate some effect from evapotranspiration. This enrichment effect is not observed in the stable isotope signatures of groundwaters in the Uley Basin, which are extremely similar to that of rainfall (Fig. 4.7) (Evans, 1997). In the case of evaporation, an increase in salinity is accompanied by an enrichment in the heavy isotopes of water (increase in δ^2H and δ^{18}O). One of the following scenarios may explain the apparent concentration of salts during recharge in the absence of a concurrent stable isotope enrichment:

1. Transpiration is the predominant process affecting groundwater salinities. Unlike evaporation, transpiration by plants has no effect on the stable isotopic signature of water, but has a similar concentration effect on salts. The large amount of native vegetation growing in the Uley Basin suggests that transpiration is an important part of the basin water balance. This may cause the significant (at least one order of magnitude) increase in groundwater chloride concentrations above that of rainfall, with no corresponding increase in stable isotope enrichment. This process is discussed quantitatively in Chapter 7.

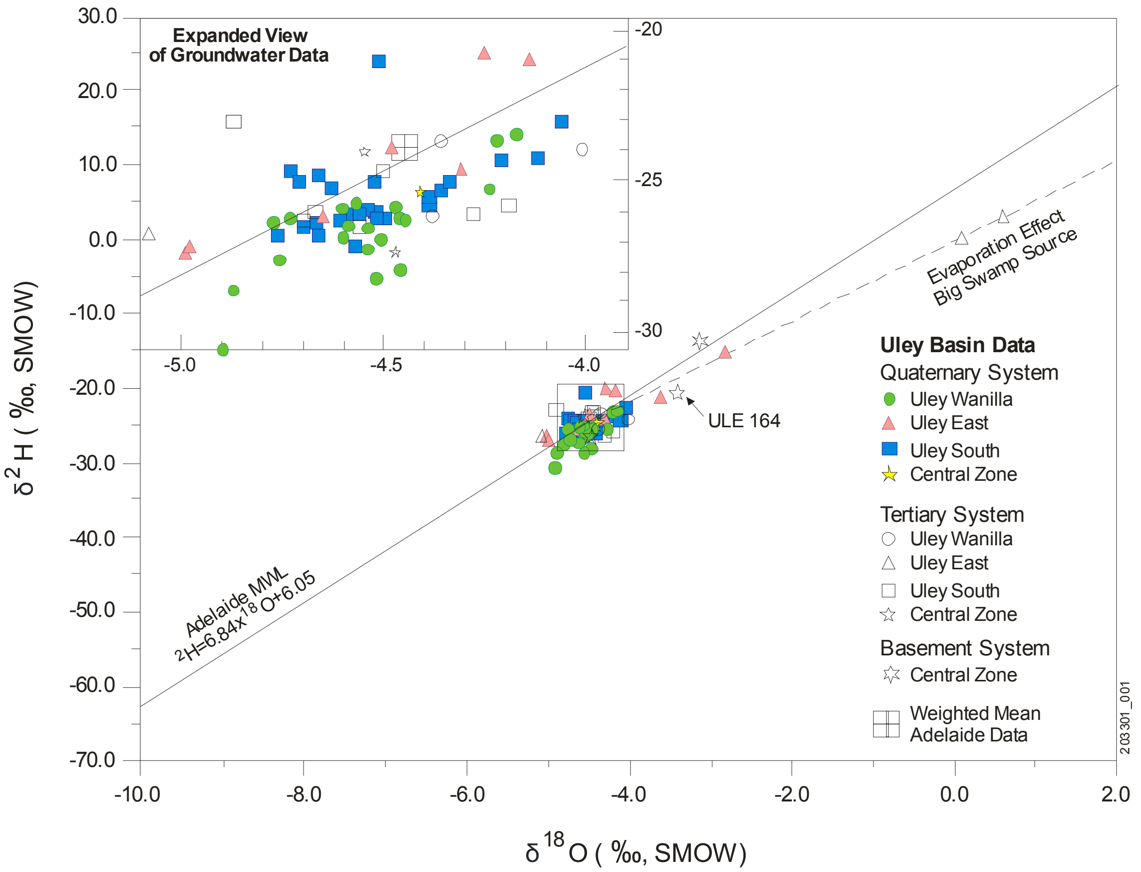


Figure 4.7. δ^2H vs δ^{18}O for Uley Basin Groundwaters (from Evans, 1997).

2. Complete (or almost complete) evaporation of incident rainfall (e.g. during summer) removes all or most water molecules preventing the enrichment effect on stable isotope signatures from being observed in the underlying groundwater. In this case,
   a. very small amounts of water, carrying very high concentrations of salt may recharge the aquifer during summer, or
   b. in the absence of adequate water remaining to allow recharge, the dissolved salts are left behind in the soil to be dissolved and re-mobilised by early winter rainfall.

The fact that there is no increase in groundwater levels during the summer, as observed by Evans (1997), supports the second point described above. Additionally, a seasonal cyclic variation in the TDS of groundwater pumped from the Uley South and Uley Wanilla production wellfields was observed by Evans (1997), with an amplitude of ~50 mg/L. This variation is common to both borefields, suggesting a common process affecting groundwater salinities in both groundwater lenses. A large decrease in TDS of the pumped groundwater was also observed to coincide with unusually high winter rainfall in 1983 and 1984. This increase in groundwater salinities in summer and lowering of groundwater salinities in winter and even more so during years with high winter rainfall provides strong evidence for the control of climate over groundwater salinities in the Uley Basin and the dynamic nature of the system (i.e. its rapidly responding nature), and suggests that mechanism two described above may be occurring. That is, evapotranspiration of a greater percentage of recharge occurs during the drier years and recharge of larger volumes of fresh water, having undergone less evapotranspiration, occurs during wet years. This seasonal and climatic control exerted by evapotranspiration on groundwater salinities is explored in more detail in Chapter 7 in relation to the potential effects of climate change.

A few groundwater samples collected by Evans (1997) from the Uley East lens and Central Zone exhibit slightly evaporated stable isotope signatures, which are likely to be due to their origin as evaporated surface water leaking from Big Swamp (see Sections 4.4.7.2 and 4.4.7.4).

4.2.2 MAJOR ION CHEMISTRY

Both rainfall in the Uley Basin and surface water from Big Swamp have seawater-like Na-Cl-Mg-SO_4 compositions. A trend in groundwater chemistry from the seawater-like composition of rainfall towards a Ca—Mg-HCO_3 water type with increasing salinity, as observed in the Uley Basin groundwaters (Fig. 4.8), is typical of groundwater moving through carbonate aquifers (Evans, 1997). In the Uley Wanilla and Uley South lenses, this transition occurs rapidly, with no intermediate compositions between the two water types being observed. This suggests that the dominant process influencing groundwater chemistry is rapid dissolution of the carbonate aquifer matrix. The exception is for the Uley East lens, where some intermediate compositions exist. This can be explained by mixing between the Ca—Mg-HCO_3 groundwaters and Na-Cl-Mg-SO_4 groundwater moving down the lens from Big Swamp and will be discussed in more detail in Section 4.4.7.2.

Figure 4.9 also shows the change in groundwater chemistry from the Na-Cl type recharge waters, plotting on the seawater-rainwater mixing line in the lower left hand corner of the graphs, towards Ca—Mg-HCO_3 type groundwaters, which plot above the seawater-rainwater mixing line on the Ca, Mg and HCO_3 graphs. This change in chemistry coincides with an increase in groundwater salinity (shown as an increase in [Cl^-]). Groundwaters plotting along the seawater-rainwater mixing line on all graphs in Figure 4.9 are behaving conservatively, only being affected by simple evaporation / dilution processes, whilst data plotting above or below the line indicate an addition or removal of the relevant ion by some geochemical process. Figure 4.9 shows that Na^+, K^+ and Br^- behave conservatively within the Uley Basin, whilst there is an addition of Ca^{2+}, Mg^{2+} and carbonate alkalinity and a depletion in SO_4^{2-}. The trends in Ca^{2+}, Mg^{2+} and carbonate alkalinity are probably due to the dissolution of Ca-carbonate and Ca-Mg-carbonate minerals, with the subsequent decrease in relative concentrations being caused by restrictions on the solubility of these minerals at higher salinities. The apparent depletion in SO_4^{2-} is likely to be due to the fact that the initial SO4/Cl ratio of rainfall is below the seawater dilution line on a SO_4^{2-} vs Cl^- diagram, although some precipitation of gypsum ($CaSO_4{\cdot}2H_2O$) during evapotranspiration of summer rainfall may also be responsible.

Groundwater data from the Tertiary aquifer system are also shown along with the Quaternary aquifer data on Figure 4.9. The Tertiary aquifer data generally plot along the same trends as the Quaternary aquifer data, further supporting a similar origin and chemical history for the two groundwater types and hence connection between the two aquifer systems.

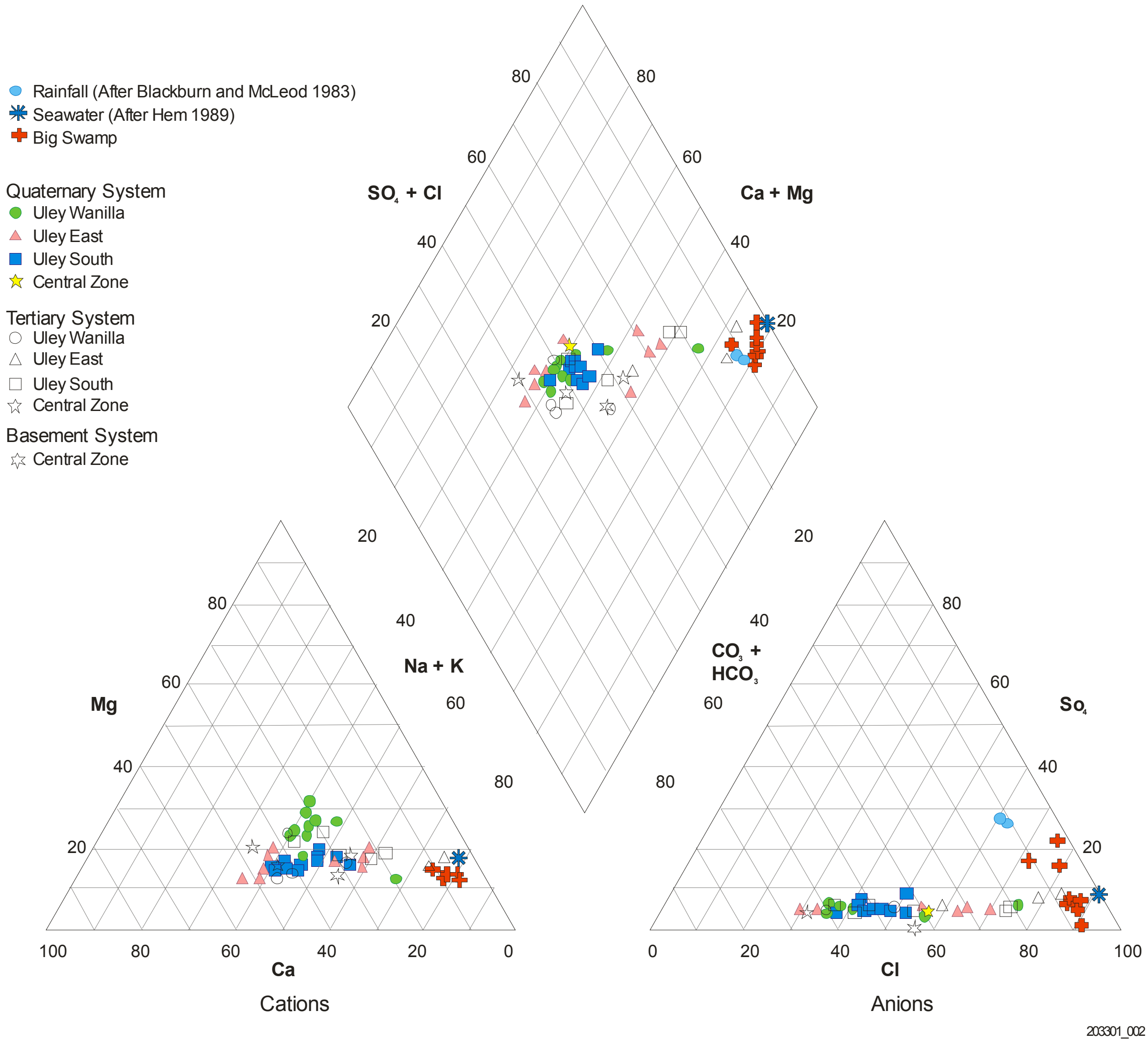


Figure 4.8. Piper diagram displaying major ion compositions of Uley Basin groundwaters (from Evans, 1997).

Some groundwater samples from the Uley Wanilla lens have distinctively high Mg concentrations (Fig. 4.9b). The cause of this different chemical composition is currently unknown, and it may be due to factors such as dissolution of high-Mg carbonate minerals (suggesting a variation in the aquifer matrix composition in this lens area), or weathering of high-Mg basement rocks. The latter process is considered unlikely as long time scales are required for this, and the presence of measurable CFC concentrations in all Quaternary groundwaters suggests relatively short residence times (see Section 4.8.3 below). This distinctive signature could be useful in identifying leakage from the Uley Wanilla lens into the Tertiary aquifer.

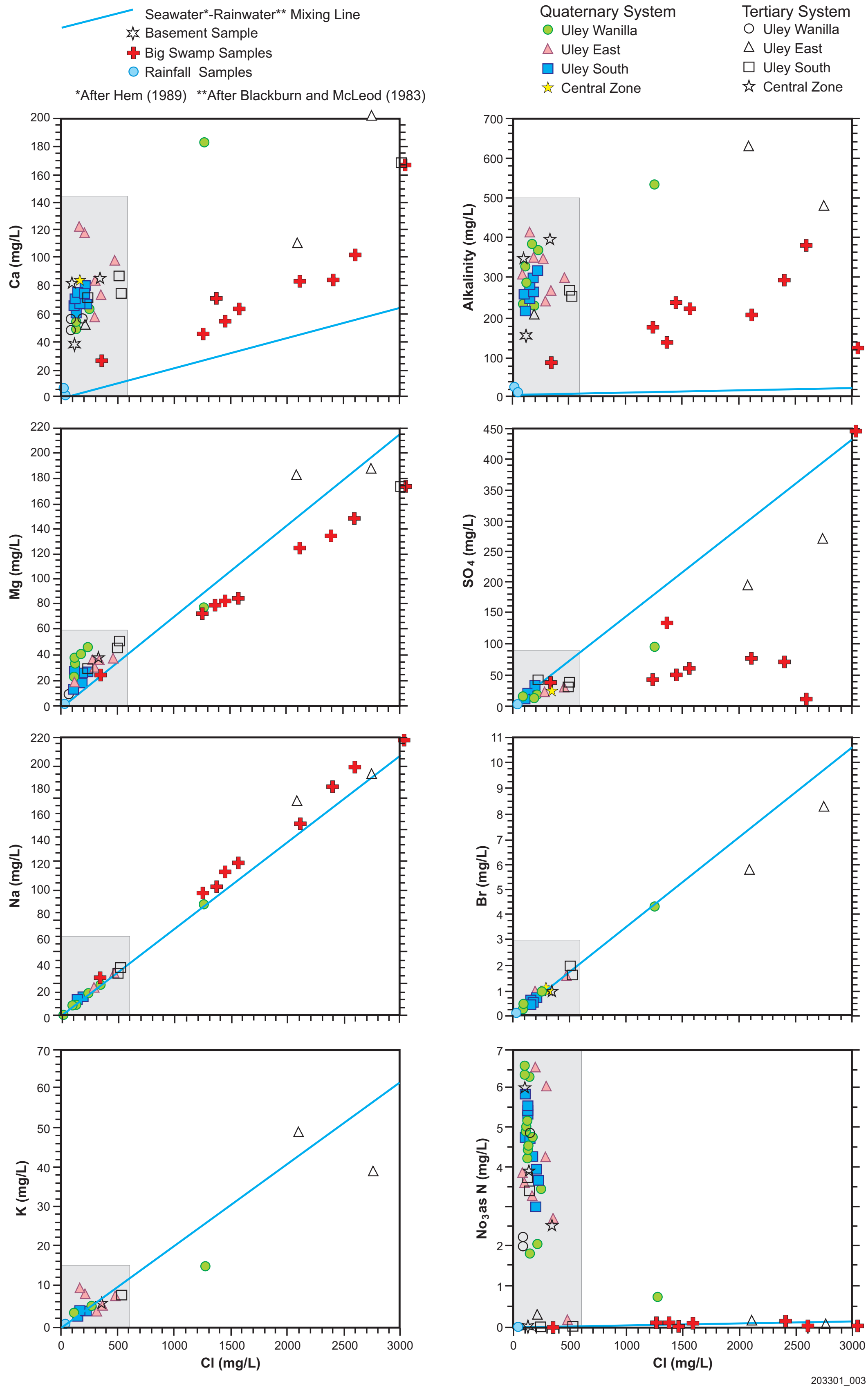


Figure 4.9a. Major ion concentrations versus chloride (Cl) concentrations for Uley Basin groundwaters (from Evans, 1997).

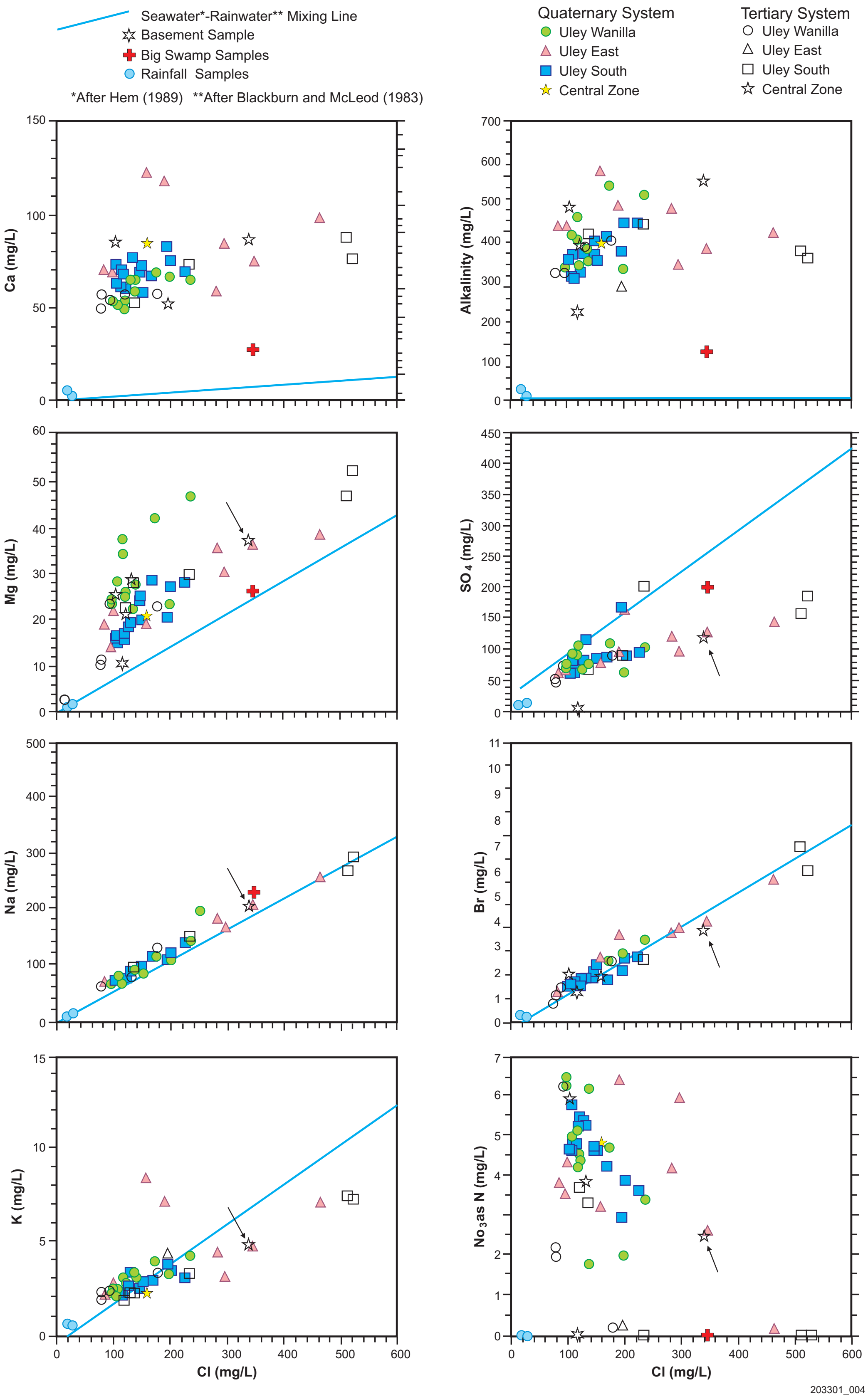


Figure 4.9b. **Major ion concentrations versus chloride (Cl) concentrations for Uley Basin groundwaters, 0–600 mg/L Cl range (from Evans, 1997).**

4.2.3 DISSOLVED CHLOROFLUOROCARBONS (CFCS)

As described in detail by Evans (1997), the concentrations of dissolved chlorofluorocarbons (CFCs) in groundwaters can be used to estimate groundwater residence times for groundwaters recharged subsequent to ~1965. Evans (1997) measured dissolved concentrations of CFCs in all Quaternary groundwaters in the Uley Basin, suggesting that all recharge to the Quaternary aquifer has occurred subsequent to 1965. Estimates of the year of recharge for the Uley Basin groundwater samples, made using a variety of assumptions ranged between 1965–87 (Evans, 1997). These groundwaters were sampled in 1995, resulting in residence times ranging between 8–30 yrs.

One important assumption in the estimation of residence times by Evans (1997) was that the water temperature at the time of recharge was ~18°C, the temperature of most groundwater samples at the time of collection. However, it was acknowledged that, since most recharge occurs during the winter months, a temperature between 9–15°C may be more appropriate, causing the estimated recharge dates to be up to six years later than reality. This is also likely to create a bias in the subsequently estimated recharge rates towards slightly higher values.

Evans (1997) identified that there is no distinct relationship between CFC concentration and sample depth below water table, leading to the conclusion that recharge rates that are highly spatially variable. However, this conclusion should be approached with caution due to the long screens of many of the piezometers sampled and resulting uncertainty in the depth from which the sample was derived. Although the depth within the screen at which each sample was collected has been clearly identified, and a low flow pumping method of sample collection was employed, the heterogeneous (karstic) nature of the aquifer and resulting preferential flow paths could mean that the water sample has been derived from anywhere along the screened interval. The estimation of recharge rates using this method is discussed in more detail in Section 4.3.

In general, there was no distinct relationship observed between CFC concentration and distance along the groundwater flow path for the Quaternary lenses (Fig. 4.10). However, as discussed further in Section 4.4.7.4, the four samples collected from the Uley East lens did show an apparent increase in groundwater residence time along the flow path. CFC data was only collected from the beginning of the flow path in the Uley Wanilla lens, meaning that a trend could not be identified for this lens even if it existed. The irregular cluster of data from the Uley South lens may be due to the fact that more than one flow path was sampled.

With the exception of one sample, collected from the region to the south of the Uley Wanilla lens, all Tertiary groundwater samples contained CFC concentrations that were close to the detection level of the method, and hence could be considered to be zero, with recharge dates prior to 1960. The estimation of recharge rates for the Quaternary aquifer from CFC concentrations is discussed in Section 4.9 below.

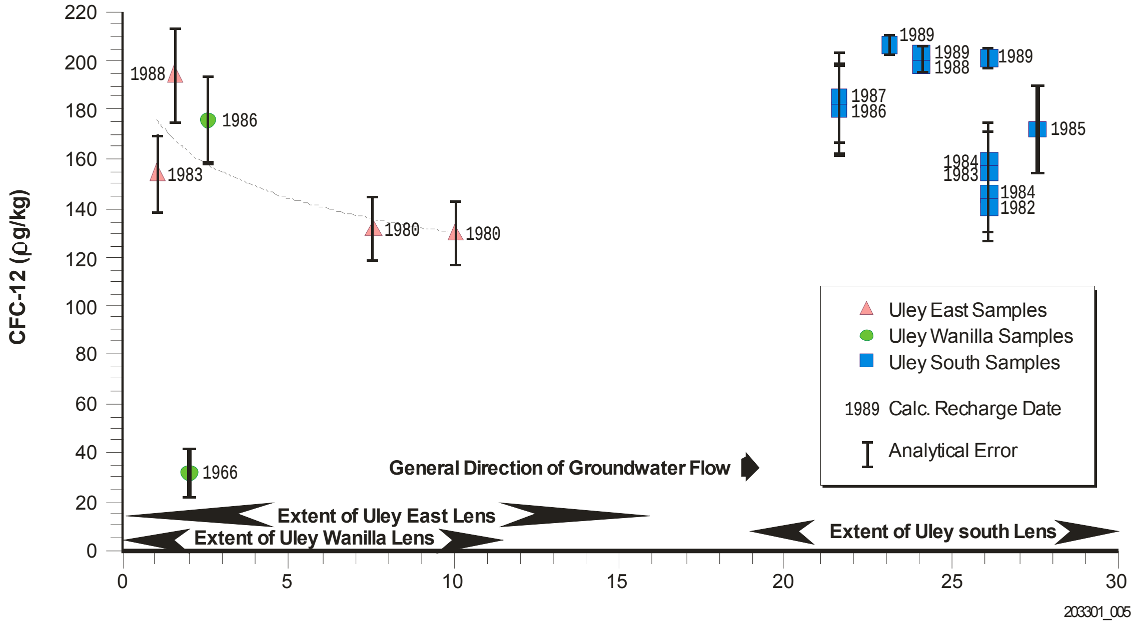


Figure 4.10. Quaternary aquifer groundwater CFC concentrations versus distance along flow path (from Evans, 1997).

4.2.4 CARBON ISOTOPES

The presence of measurable CFC concentrations in all Quaternary aquifer groundwater samples, hence implying groundwater residence times less than approximately 40 yrs (Evans, 1997), indicates that ^{14}C of dissolved inorganic carbon (DIC), which can be used to estimate groundwater residence times between ~2000–40 000 yrs, will not be useful as an indicator of residence time in this system. Some Tertiary aquifer groundwater samples, where the CFC concentrations are at or below detection levels may be an exception. However, carbon isotope signatures, particularly $\delta^{13}C$, can be used to provide useful qualitative information about groundwater flow and interactions with carbonate aquifer material.

The $\delta^{13}C$ signature of DIC in groundwater recharge would normally range between ~-22 ‰ and -11 ‰, with a ^{14}C content of close to 100% modern carbon (pmC) (Leaney & Allison, 1986; Clark & Fritz, 1997). Interaction with carbonate minerals ($\delta^{13}C \approx 0$ ‰) causes an increase in $\delta^{13}C$ of groundwaters. The $\delta^{13}C$ signatures of groundwater samples from the Uley Basin, collected by Evans (1997) ranged between -12.9 ‰ and -3.7 ‰ (Fig. 4.11). The more negative values (< -10 ‰) are interpreted to indicate recent or "enhanced" recharge, whilst the increasingly positive values are interpreted to indicate an increasing influence of carbonate mineral dissolution and hence longer groundwater residence times (Fig. 4.11). Figure 4.11 shows that an increase in $\delta^{13}C$ as a result of interaction with carbonate minerals is accompanied by a decrease in ^{14}C content from a "modern" recharge value close to 100 pmC towards 0 pmC, the value derived from dissolution of "dead carbon" contained in a marine carbonate.

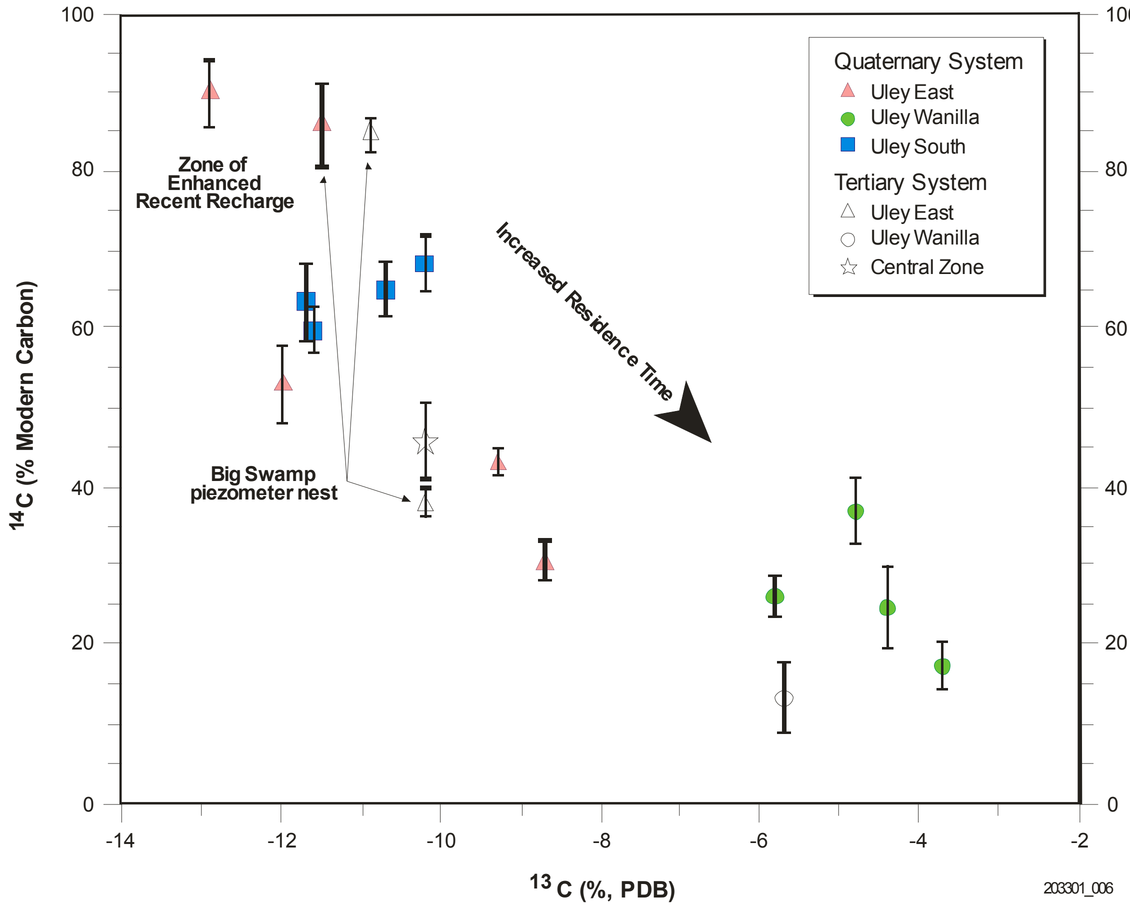
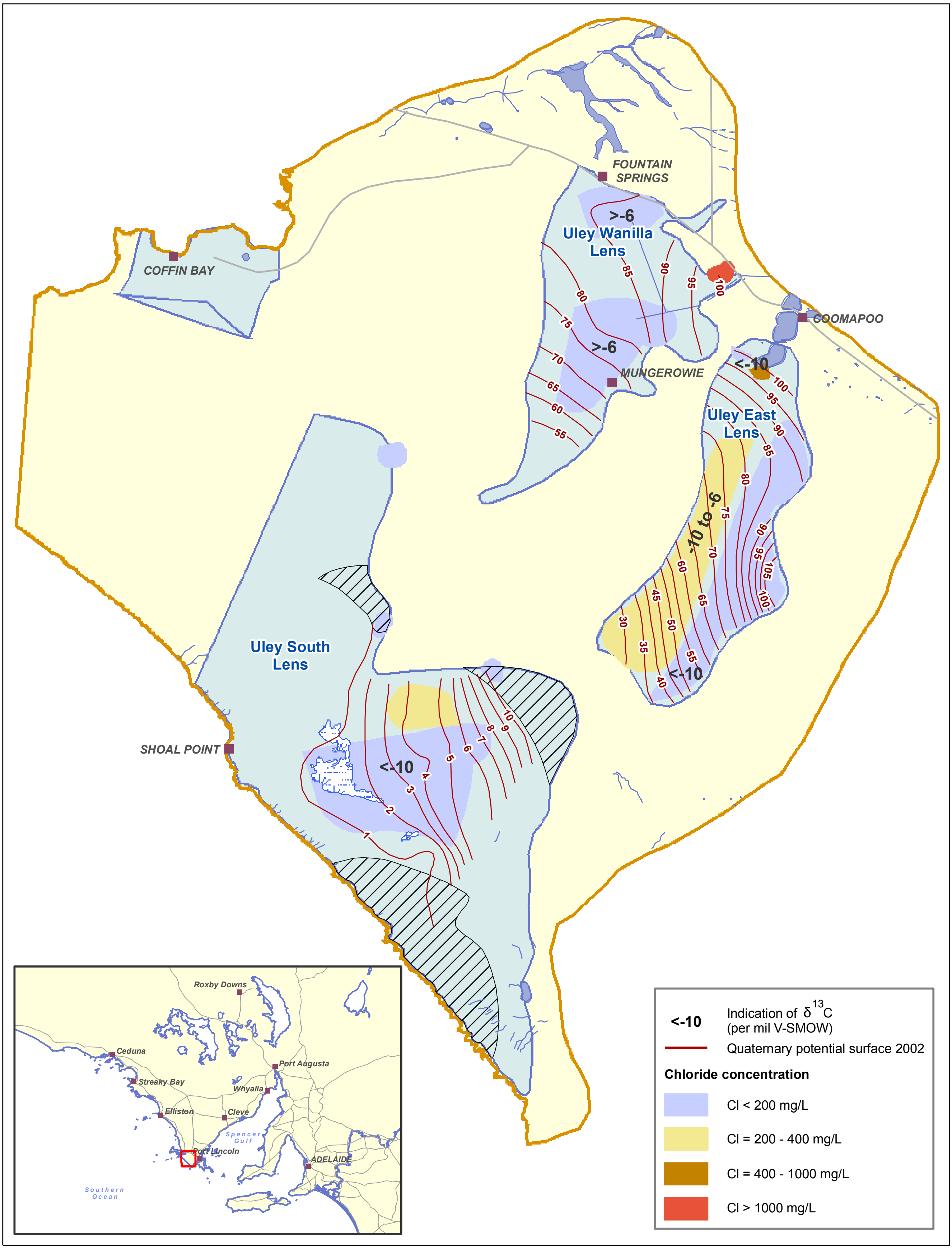


Figure 4.11. ^{14}C vs $\delta^{13}C$ **for Uley Basin groundwaters (from Evans, 1997).**

The Quaternary aquifer groundwaters of the Uley Basin cover the full spectrum of $\delta^{13}C$ and ^{14}C values (Fig. 4.11), indicating a large amount of spatial variability in recharge rates and/or groundwater residence times/flow rates. For the purpose of developing the conceptual model, the carbon isotope data are divided into the following groups according to the implications for groundwater flow processes:

- (1) $\delta^{13}C$ < -10 ‰: Indicative of modern or "enhanced" recharge (short groundwater residence times and/or high recharge rates).
- (2) $\delta^{13}C$ > -6 ‰: Indicative of highly evolved groundwaters, with relatively long residence times and little influence from modern recharge (i.e. low recharge rates).
- (3) -10 ‰ < $\delta^{13}C$ < -6 ‰: Groundwaters that are intermediate between the two above scenarios.

These groups are shown on Map 2 and compared with groundwater salinity ([Cl^-]) zones. It would be expected that, in the absence of any other process affecting groundwater salinities, the more negative $\delta^{13}C$ values (Groups 1 and 3) would be associated with low [Cl^-] due to the freshening effect of enhanced groundwater recharge. It can be seen from Map 2 that this is not always the case, indicating some other processes affecting groundwater salinities. The relationship between $\delta^{13}C$ and [Cl^-] will be discussed in more detail for the individual groundwater lenses in subsequent sections.



Map 2. Groundwater chloride concentrations and $\delta^{13}C$ in Quaternary groundwater sediments

Locality
Drainage
Road
Waterbody
Swamp
Uley Basin
Quaternary groundwater lens
Tertiary clay absent

N

0 1.25 2.5 5 km

Map Production: Resource Information Group
Department of Water, Land and Biodiversity Conservation

Map Projection: MGA Zone 53
Map Datum: GDA94.

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

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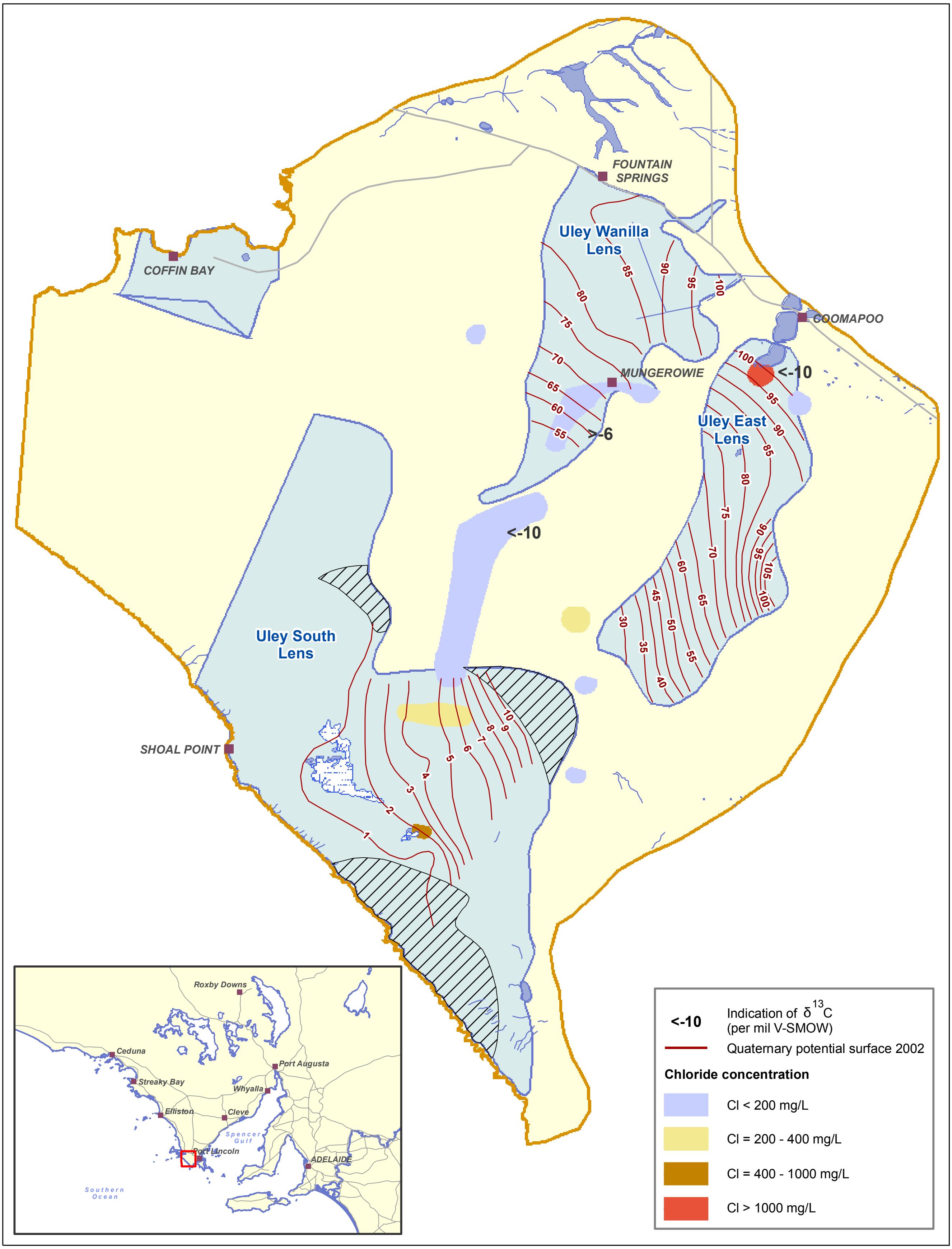
Carbon isotope signatures were measured on four Tertiary aquifer groundwater samples by Evans (1997). These are also shown on Figure 4.11 and Map 3. The Tertiary aquifer data also exhibit the full range of ^{14}C and $\delta^{13}C$ values and lie approximately along the same trend on Figure 4.11 as the Quaternary aquifer data samples. This similarity strongly suggests connection between the two aquifer systems. In some cases the Tertiary aquifer data lie slightly below the trend for the Quaternary aquifer (i.e. lower ^{14}C values for the same $\delta^{13}C$ values), possibly indicating significantly higher groundwater residence times for the Tertiary aquifer samples, although actual residence times will be difficult to derive due to the scatter in the data. Individual data points will be discussed in more detail in Section 4.10.

4.2.5 KEY CONCLUSIONS FROM THE GENERAL OVERVIEW OF HYDROCHEMISTRY AND ISOTOPIC SIGNATURES FOR THE ULEY BASIN

- Similar chemical histories and origins for the Quaternary and Tertiary groundwaters are indicated by:
  - Similar relationships between TDS and [Cl^-].
  - Similar chemical trends on major ion vs [Cl^-] diagrams.
  - Similar trend on ^{14}C vs $\delta^{13}C$ diagram.
- All Quaternary groundwaters have been recharged subsequent to 1965, indicating residence times up to 30 yrs.
- Tertiary aquifer groundwaters have generally been recharged prior to 1960, indicating groundwater residence times greater than 35 yrs.
- CFC or carbon isotope data may be used to determine approximate minimum leakage rates.
- There is large spatial variability in groundwater recharge rates and/or groundwater residence times / flow rates in the Quaternary aquifer.
- The long screens of some observation wells sampled for CFCs make conclusive estimations of recharge rates difficult. However, the presence of CFCs in the Quaternary groundwater samples and the range of values observed suggest that the methodology will be extremely useful if this issue can be resolved. Revisitation of this methodology using a carefully designed observation well network (short screens and a number of piezometer nests) may be recommended if the groundwater flow modelling identifies a need to better constrain recharge estimates.
- Due to the short residence times of the groundwaters in the Quaternary lenses of the Uley Basin, carbon isotopes are not useful in estimating groundwater residence times in these systems. Longer residence times in the Tertiary aquifer may mean that carbon isotopes have some application in this system, however.
- Relatively low [Cl^-]s suggest that there is low ET of rainfall prior to recharge, compared with other parts of South-Eastern Australia. Stable isotope signatures support this.
- However, there is still a significant increase in groundwater [Cl^-] above the rainfall value.
- Almost complete evapotranspiration of incident rainfall during summer and predominantly transpiration during winter is the rainfall/recharge mechanism that is most consistent with observed changes in water table, salinity and stable isotope data.
- This process is common to both the Uley South and Uley Wanilla bore field areas.



Map 3. Groundwater chloride concentrations and $\delta^{13}C$ in Tertiary sediments

Locality
Drainage
Road
Waterbody
Swamp
Uley Basin
Quaternary groundwater lens
Tertiary clay absent

N

0 1.25 2.5 5 km

Map Production: Resource Information Group
Department of Water, Land and Biodiversity Conservation

Map Projection: MGA Zone 53
Map Datum: GDA94.

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

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- The Quaternary aquifer system is dynamic and responds rapidly to seasonal and longer-term changes in rainfall.
- Mixing between chemically "evolved" groundwater and Na-Cl type groundwater from Big Swamp is inferred for the Uley East lens.
- The occurrence of high Mg groundwaters, characteristic of the Uley Wanilla Quaternary groundwater signature could be useful to investigate leakage from the Uley Wanilla lens into the Tertiary aquifer.

4.3 GENERAL RECHARGE INFORMATION

4.3.1 REVIEW OF PREVIOUS METHODS USED

A number of estimates of recharge rates have been made for the various groundwater lenses of the Uley Basin over the last 70 yrs (Table 4.1). The majority of early estimates were based on the knowledge of the water balance at the time.

Table 4.1. Recharge estimates from various studies for the three Quaternary lenses (from Evans, 1997).

Study [method]	Uley South	Uley Wanilla	Uley East
Buick (1941)		350	350
Segnit (1942)		145	145
Morton & Steel (1968)	83		
Sibenaler (1976)	40		
Barnett (1978) [hydrograph method / limiting winter rainfall]	105		
EWS (1984)	72	72	72
Evans (1997) [chloride mass balance]	64–71	33–51	
Evans (1997) [water balance analysis]	157	85	76
Evans (1997) [Water balance with salt water interface consideration]	78		
Evans (1997) [hydrograph fluctuations with specific yield calculations]	46	20	11
Evans (1997) [Chlorofluorocarbon (CFC) concentrations]	<200	<50	<75

The method of Barnett (1978) was based on a hydrograph method to estimate recharge to the Uley South lens. Winter rainfall was plotted against rise in water table to give a limiting winter rainfall for recharge to occur of 217 mm. Average winter rainfall was estimated to be 322 mm/y and, based on this, average winter recharge was estimated to be 105 mm. The limitation of this method is that it relies upon a linear relationship between change in groundwater level and winter rainfall. As in any natural system, particularly one with such heterogeneity as the Uley Basin, the data is most likely to be broadly scattered around a linear trend. This is observed in the data presented by Barnett (1978) and hence a significant degree of uncertainty and averaging is inherent in the derivation of a linear relationship.

Evans (1997) used a range of indirect methods to estimate average annual recharge to the Uley Wanilla, Uley East and Uley South lenses of the Uley Basin. These included the groundwater flow budget (Darcy flow analysis), rainfall-water level change relationships, the chloride mass balance method and groundwater chlorofluorocarbon (CFC) contents. Each method has inherent assumptions and limitations, but it was considered that close agreement between a range of methods can improve confidence in the estimates made. The methods and their broad outcomes are summarised briefly here and discussed in more detail in following sections on the individual groundwater lenses:

- Both the groundwater flow budget and the chloride mass balance methods provide very broad scale estimates of recharge due to the requirement to average parameters such as aquifer hydraulic properties, rainfall, rainfall chloride concentrations, and groundwater chloride concentrations over very large areas.
- The analysis of rainfall-water level change relationships provided good qualitative information on Quaternary aquifer hydraulics. However, it was found that, due to the rapid aquifer response to rainfall, the monthly groundwater level monitoring program could not properly resolve the peaks that resulted from rainfall recharge events, resulting in an underestimate of recharge. Another limitation of this method is the heterogeneity in specific yield characteristics of the aquifer, making quantitative interpretation based on average characteristics highly inaccurate.
- Based on analysis of the rainfall intensity – groundwater level change relationship, Evans (1997) proposed that, for there to be a net rise in groundwater level in the Quaternary aquifer during the year, there needs to be at least 10 days of rainfall greater than 10 mm during the May–September period.
- Evans (1997) identified two types of water table responses to rainfall, indicative of the heterogeneous nature of recharge across the Uley Basin. The first response is immediate (within hours) and short-lived, a sharp rise in water level following significant rainfall events, followed by a steady decay. This response is characteristic of wells close to zones of rapid recharge via flow down sinkholes (Fig. 4.12). The second response is delayed by up to days and damped, with a more rounded peak of smaller magnitude. This response is characteristic of wells located further away from zones of preferential recharge. The decay profiles of both types of water level curve are similar, suggesting that groundwater flow characteristics are fairly uniform across the region. Classification of water level hydrographs into “rapid response” and “delayed response” categories, and mapping of these to compare with CFC, $\delta^{13}C$, $[Cl^-]$ and sinkhole distribution maps would provide a good basis for mapping zones of preferential recharge. Unfortunately, the first type of profile cannot be properly identified or quantified through a monthly monitoring program.
- Interpretation of chlorofluorocarbon (CFC) concentrations in groundwater can provide point estimates of recharge and therefore gives an indication of the spatial variability in recharge across the Quaternary lenses. Evans (1997) compared CFC data from the Uley Basin groundwater lenses with modelled curves of recharge rates for given sample depths and CFC concentrations. However, an accurate estimation of recharge rate by this method requires a well-constrained estimate of sample depth. As many of the wells sampled, particularly from the Uley South lens, had extremely long screened intervals (up to 12 m), only very broad ranges of recharge rates could be assumed in many cases. An extremely low pumping rate (~10 L/min) was used to minimise the possibility of this. However, despite this, the known presence of preferential flow in the aquifer could mean that sampled water may have come from anywhere along the screened interval. If the majority of the water sampled can be assumed to originate from the depth at which the pump was placed, these recharge rate estimates can be narrowed. As described above, if more constrained estimates of recharge are required, it may be necessary to install observation wells with narrower screens so that CFC and Cl data can be used more reliably to estimate recharge.

Figure 4.12a. Sinkhole in the Uley Wanilla lens area.

Figure 4.12b. Large sinkhole in the central Uley South area.

Figure 4.12c. Large sinkhole in the central Uley South area.

Figure 4.12d. Large sinkhole in the central Uley South area.

Relatively good agreement between the chloride mass balance and water balance (with seawater interface consideration for the Uley South lens) methods of Evans (1997) provides confidence in approximate ranges of estimates for average annual recharge rates across the Uley Basin lenses. The CFC data expand on this by providing point estimates of average annual recharge and hence an indication of the spatial variability in recharge across the lenses. Additionally, a reasonable agreement between the methods of Evans (1997) and the limiting winter rainfall method of Barnett (1978) suggest that the latter method may be useful in providing temporally varying estimates of recharge for the lenses. The applicability of this method will be explored more fully in Section 5.1.

4.3.2 KEY CONCLUSIONS FROM GENERAL REVIEW OF PREVIOUS RECHARGE STUDIES

- The groundwater flow budget and chloride mass balance methods provide good estimates of average annual recharge across the individual groundwater lenses.
- Analysis of rainfall-water level change relationships provided good qualitative information, but monthly sampling is not frequent enough to detect actual water level maximums and minimums, leading to an under-estimate of recharge.
- Classification of water level hydrographs into “rapid response” and “delayed response” categories, and mapping of these to compare with CFC, $\delta^{13}C$, [Cl^-] and sinkhole distribution maps would provide a good basis for mapping zones of preferential recharge.
- CFC data provides good point estimates of recharge, and hence an indication of spatial variability. However, the quantitative interpretation is currently limited by the long screen lengths of the observation wells available for sampling. If more constrained point estimates of recharge are required, installation and sampling of nests of piezometers with shorter screens may be recommended.
- A reasonable agreement between the methods of Evans (1997) and the limiting winter rainfall method of Barnett (1978) suggest that the latter method may be useful in providing temporally varying estimates of recharge for the lenses.

4.4 THE HYDROGEOLOGICAL CONCEPTUAL MODEL

4.4.1 BASEMENT UNITS

Limited information exists on the basement units of the Uley Basin, but they are believed to consist of both weathered and un-weathered Archaean quartz feldspar gneiss and feldspathic quartzites, with irregular occurrences, salinities and yields. The basement system is also believed to have negligible interaction with the Quaternary aquifer system, although its structure has a significant control over aquifer thicknesses and geometries. For example, the Uley Wanilla and Uley South lenses are located in one basement trough, whilst the Uley East lens is located in a second trough to the east of the first (App. A; Figs A.1–A.7). These troughs were cut into the basement rock during pre-Tertiary times and the lenses have longitudinal margins that are controlled by basement highs. In the Uley South region, the basement structure controls the dimensions of the Tertiary Sand aquifer, but only the eastern and northern margins of the Quaternary system. The longitudinal basement highs outcrop as wave cut platforms at various points along the coastline (Map 1).

4.4.2 TERTIARY SAND AQUIFER

4.4.2.1 General Characteristics

Directly overlying the basement rocks, and known to be over 60 m thick in the basement trough that forms the western part of the Uley South lens, are Tertiary sediments, consisting of fluvial sands, clays and grits with some lignitic lenses. The main aquifer in this sequence is the Tertiary Sand, comprising sands and gravels and is silty and carbonaceous at its base. Groundwater production from this aquifer is problematic due to its unconsolidated fine sandy nature.

The aquifer is believed to occur mainly in the Uley South region and monitoring is predominantly limited to this portion of the study area, where it lies mostly below sea level (Evans, 1997). Its extent is largely unknown in the Uley Wanilla and Uley East area. However, a series of nested wells adjacent Big Swamp includes one well screened in the top of the Tertiary Sand and indicates a downward hydraulic potential between the Quaternary and Tertiary aquifers in that region. The Tertiary Sand is the water table aquifer in the region between the Uley Wanilla / Uley East and Uley South zones of the study area (App. A). Map 1 shows our current understanding of the extent of the Tertiary Sand aquifer.

4.4.2.2 Water Sources

Potential sources of water to the Tertiary Sand aquifer are:

1. Recharge through outcropping Tertiary Clay sediments in the northern portion of the study area (Map 1).
2. Direct recharge to the Tertiary Sand in areas of the central portion of the study area where the Quaternary limestone is dry.
3. Leakage from the Quaternary limestone aquifer through the Tertiary Clay aquitard, or in areas where the Tertiary Clay is absent (Map 1).
4. Lateral inflow from north of the study area.

4.4.2.2.1 Recharge in the Northern Part of the Study Area

Due to a lack of knowledge of the extent and thickness of the Tertiary Sand aquifer in the northern part of the Uley Basin, as well as the thickness and properties of the outcropping Tertiary Clay, inflows to the aquifer in that region are unknown.

However, recharge from Big Swamp to the Tertiary Sand aquifer is suggested by high groundwater salinities ([Cl-]) measured in the nested Tertiary observation wells at the southern extent of Big Swamp. This, along with the evaporated stable isotope signatures (Fig. 4.7) and Na-Cl type chemical composition of the groundwater (Fig. 4.8), is consistent with inflow of evaporated water from the wetland (Map 2). Cross-section II’ (App. A) suggests that the shallower of the two Tertiary wells may be screened within a sandy interval of the Tertiary Clay or a sand-clay inter-tonguing interface in this zone, whilst the deeper is screened in the top of the Tertiary Sand aquifer.

CFC and carbon isotope data from the observation well nest at the southern extent of Big Swamp provide some useful information about vertical groundwater flow in this area (Table 4.1). The groundwater in the Quaternary aquifer at this location has a residence time, inferred from CFC concentrations, of ~9 yrs, whilst the underlying groundwater in the Tertiary aquifer contains CFC concentrations that are close to the detection limit for the method and hence unreliable for dating (residence time > 45 yrs). In the case of the Tertiary units, 14C may provide more information on groundwater residence times. The carbon isotope data from both the Quaternary and Tertiary aquifer wells shown in Table 4.2 generally plot along the trend of decreasing 14C with increasing δ13C on Figure 4.11. Groundwater from the Quaternary well has a signature that is consistent with enhanced recharge, as does that from the shallower Tertiary well, which is consistent with groundwater having moved fairly rapidly through the Quaternary limestone into the clay (i.e. with little time to dissolve aquifer carbonate minerals).

Table 4.2 Groundwater chloride, CFC and carbon isotope data from the piezometer nest at the southern extent of Big Swamp (after Evans, 1997).

Obs No.	Aquifer	Screen depth (m)	[Cl-] mg/L	CFC age	$\delta^{13}C$ (‰ VSMOW)	^{14}C
ULE199	Quaternary	2–5	463	1986	-11.5	85.8
ULE198	Tertiary	21–24	2754	<1940	-10.9	84.5
ULE195	Tertiary	28–31	2092	1954	-10.2	38.1

The δ13C signature of the deeper Tertiary Sand well, with a screen only 4 m below that of the shallower Tertiary Clay well, also suggests little evolution in the Quaternary aquifer (little carbonate mineral dissolution indicated by similar δ13C), but a much greater residence time in the Tertiary Sand aquifer (much lower 14C content). Based on a simple extrapolation of the main evolutionary trend to obtain an Ao value, and application of the 14C decay equation, the residence time of the Tertiary Sand aquifer sample could be of the order of 3000–6500 yrs, compared with the Tertiary Clay sample, which is relatively modern on the time scale of ^{14}C. This interpretation suggests that vertical groundwater flow between the two piezometer screens is minimal or very slow. One possible hypothesis for the origin of the water in the Tertiary Sand is that this aquifer is relatively thin and isolated in this region below Big Swamp and that very slow leakage of saline water from Big Swamp is the main source of recharge. Such a conclusion and hypothesis should be considered preliminary and additional field data should be collected to further investigate this, however, if it is considered in the important in the development of the numerical model.

$$t = -8270 \ln \frac{A}{A_o} \qquad (4.1)$$

t = residence time (yrs), A = ^{14}C activity (pmC), A_o = initial ^{14}C activity (pmC), –8270 is the inverse of the ^{14}C decay constant (-)

4.4.2.2.2 Recharge in the Central Part of the Study Area

As shown on Maps 3 and 4, groundwater sampled from observation well ULE169 in the central portion of the study area, has:

- a relatively negative δ^{13}C that is consistent with little interaction with the Quaternary limestone aquifer. This differs from the “evolved” signature of up-gradient Tertiary aquifer groundwater below the Uley Wanilla lens (Maps 2 and 3; Fig. 4.11).

- a recharge date of 1975, inferred from CFC concentrations, which is recent compared with all other Tertiary unit samples with the exception of groundwater extracted from the Tertiary Clay to the west of the Uley Wanilla lens.

The above observations suggest that, in the central part of the study area, to the south west of the Uley Wanilla lens, a significant amount of recently recharged groundwater may have mixed with groundwater flowing down from the Uley Wanilla lens area. Cross section HH' (App. A) shows that the Tertiary Clay is present, but relatively thin in the vicinity of observation well ULE169, and that a slight depression may occur in the clay at this location. This could lead to accumulation of locally incident recharge above the clay at the location of ULE169, before infiltration to the Tertiary Sand below. Additional sampling in other parts of the central portion of the study area would be required to determine whether this process is more widespread. For example, a similar depression in the Tertiary Clay is shown at the location of observation well ULE169 on cross section DD' (App. A).

4.4.2.2.3 Leakage from the Quaternary Limestone Aquifer

Leakage from the southern boundaries of the Uley Wanilla and Uley East lenses into the Tertiary Sand aquifer has been suggested by Evans (1997) to occur through the Tertiary Clay aquitard, or windows in this aquitard. The areas where the Tertiary Clay is known to be absent are shown on Map 1, and other windows that have not yet been observed may also exist. Such vertical leakage is considered to be the best explanation for the Quaternary limestone aquifer becoming unsaturated at the southern extents of the Uley Wanilla and Uley East lenses despite a consistent southerly slope in the aquifer, although there is a paucity of physical evidence to date to support this assumption.

Evidence for leakage from the Quaternary aquifer can be seen in one Tertiary aquifer observation well, ULE164, located in the central zone to the south west of the Uley East lens, which has a similar geochemical and stable isotope signature to the Uley East Quaternary groundwaters that have been influenced by recharge from Big Swamp (see Section 4.4.7.2 for explanation of this) (Figs. 4.7–4.9). This leakage may have occurred anywhere along the groundwater flow path from Big Swamp, as well as at the southern extent of the Uley East lens.

It is also possible that some downward leakage from the Quaternary aquifer into the Tertiary Sand also occurs along the entire lengths of the Uley Wanilla and Uley East lenses. An "evolved" carbon isotope composition of the Tertiary aquifer groundwater below the Uley Wanilla lens, similar to that in the overlying Quaternary aquifer (Maps 2–3; Fig. 4.11), as well as similar groundwater [Cl-]s (Maps 2–3) suggests some leakage in this area. In the Uley South lens, similar groundwater [Cl-], in the 200–400 mg/L range may also suggest leakage between the Quaternary and Tertiary aquifers (see yellow zone, Maps 2–3). More sampling of the Tertiary aquifer is required to further investigate the occurrence of inter-aquifer leakage if this is considered to be important for the numerical modelling process.

4.4.2.2.4 Lateral Inflow from North of the Study Area

Groundwater inflow to the Tertiary Sand aquifer from the region to the north of the Uley Basin is considered to be possible, but no data currently exists to enable this hypothesis to be confirmed or refuted, nor for it to be quantified.

4.4.2.3 Water Outflows

The Tertiary Sand aquifer discharges to the Southern Ocean at the south-western boundary of the Uley Basin, and this is thought to be the only groundwater discharge for that aquifer. Hydraulic connection with the ocean is supported by the fact that oscillations observed in Tertiary Sand hydrographs coincide with tidal fluctuations (Evans, 1997). There is currently insufficient information to calculate the volume of the discharge flux from the Tertiary aquifer with any certainty. At the coastline, the Tertiary Sand may lie greater than 30 m below sea level and hence, discharge would be influenced by density effects at the seawater interface.

Other possible outflows for the Tertiary Sand aquifer are via (i) downward leakage to the basement units (e.g. via fractures in the basement) and (ii) upward leakage to the Quaternary aquifer. There is no observation data available to support or refute the occurrence of leakage to the basement and it is currently considered that such leakage, if it occurs, is likely to represent an insignificant portion of the water budget for the aquifer (Evans, 1997).

Groundwater in the Tertiary Sand is believed to be under pressure in the Uley South lens, but it is suggested by (Morton & Steel, 1970) that the aquifer is of a leaky type due to the semi-permeable nature of the overlying Tertiary Clay aquitard. This raises the possibility of upward flow between the Tertiary Sand and Quaternary aquifer in regions where there is an upward hydraulic gradient. Few piezometer nests are available to identify where such upward hydraulic gradients exist. However, the few that do exist suggest that an upward hydraulic gradient may occur down gradient of cross section BB' in the Uley South lens area. The head difference observed here is ~0.2 m. Additional piezometer nests would be required to further map the occurrence of upward hydraulic potentials. An area of higher salinity (high [Cl^-]) that occurs in both the Quaternary and Tertiary aquifers below the Uley South lens (yellow areas on Maps 2–3) could be indicative of such upward flow. However, a relatively recent CFC inferred recharge date for this groundwater in the Quaternary (1985) compared with the Tertiary aquifer (1951–53) suggests that such leakage is minimal in this region.

4.4.2.4 Groundwater Flow

Groundwater flow in the Tertiary Sand aquifer is generally from north-east to south-west, similar to that in the Quaternary aquifer system, following the slope of the underlying basement structure. Limited observations of the Tertiary Sand aquifer in the Uley South region suggest that hydraulic gradients are similar to those in the overlying Quaternary system (Evans, 1997). Hydraulic heads of the two aquifers are coincident in the northeastern portion of the Uley South region, where the Tertiary Clay is absent. Sibenaler (1976) suggested that the Quaternary and Tertiary systems are hydraulically connected in that region. Evans (1997) suggests that the seasonal variations observed in Tertiary Sand hydrographs across areas where the Tertiary Clay is present may reflect the direct pressure loading of the seasonal variation in the water level of the unconfined aquifer.

4.4.2.5 Aquifer Properties

The Tertiary Sand has a large storage capacity, but poor to moderate yields. According to Morton and Steel (1970), lateral variation in the permeability of the Tertiary Sand aquifer can be expected due to the fluviatile nature of its deposition. However, information on the hydraulic properties of the Tertiary Sand aquifer is currently limited to observations from one borehole. At borehole PT1 in the Uley South region, the aquifer is estimated to have a transmissivity of 682 m^2/day and a storativity of 0.007 (Morton & Steel, 1970).

4.4.2.6 Groundwater Salinity

Pre-development groundwater salinity in the Tertiary Sand aquifer is less well understood than for the Quaternary groundwater lenses. Below the Uley South lens, the pattern of 1950s Tertiary groundwater salinities reflected those in the overlying Quaternary aquifer, although salinities in the Tertiary are generally at least 100–200 mg/L higher, ranging from 540–~1200 mg/L (Evans, 1997). The salinities were also similar to those in the southern parts of the Quaternary Uley Wanilla and Uley East lenses, possibly supporting the theory of inflow from these lenses. Below the north-eastern end of the Uley East lens, groundwater salinities greater than 1000 mg/L in the Tertiary Sand are considered to be caused by inputs from Big Swamp (see Section 4.4.2.2.1; Evans, 1997). As described earlier, a downward hydraulic gradient between the Quaternary and Tertiary aquifers in this region and other hydrochemical evidence support this conclusion.

Anomalously high Tertiary groundwater salinities (1200–3300 mg/L) below the western portion of the Uley South lens have been attributed to their occurrence in an isolated part of the Tertiary aquifer, although the direct cause is unknown (Evans, 1997).

Seven Tertiary aquifer wells sampled in the 1950s–60s drilling program were re-sampled by Evans (1997). All of these occur below the central and Uley South regions. Of these, groundwater salinities in all but two wells have remained relatively un-changed. An increase from 857–1255 mg/L is observed in one well below the central part of the Uley South Lens, and a decrease from 897–531 mg/L is observed below the north western margin of the Uley South lens.

4.4.2.7 Summary of Tertiary Sand Conceptual Model

The details of the conceptual model for the Tertiary Sand aquifer are summarised on Figures 4.13–4.15.

General Characteristics

- Comprises sands and gravels with a silty and carbonaceous base.
- Tertiary Sand extent below Uley Wanilla and Uley East lenses largely unknown, but it may be thin or discontinuous.
- Some Tertiary Sand observed in nested wells below southern extent of Big Swamp.

Water Inflows

- Recharge to Tertiary Sand in northern part of study area is unknown.
- Leakage from Big Swamp to Tertiary Sand inferred from salinity ([Cl^-]) and stable isotope data. This water is derived from lateral inflow from higher in the Big Swamp catchment area.
- Tertiary sand may be thin or occur in isolated pockets in the region below Big Swamp, with long-term slow leakage of saline water occurring into it.
- Some recharge to Tertiary Sand occurs in central zone, to south west of Uley Wanilla lens. This may be due to a depression in the Tertiary Clay that funnels recharge to this point. If so, similar depressions could have this effect elsewhere, for example at

observation well ULE163, which lies between the southern tips of the Uley Wanilla and Uley East lenses.

- Leakage from southern extents of Uley Wanilla and Uley East Quaternary lenses into Tertiary Sand inferred from simple mass balance argument.
- Leakage from Quaternary aquifer to Tertiary Sand may occur anywhere along Uley Wanilla and Uley East flow paths. Hydrochemical evidence for this is observed at the southern end of Uley Wanilla and south western corner of the Uley East.
- More sampling is required to properly investigate inter-aquifer leakage.

Water Outflows

- Discharge to the Southern Ocean considered to be the major outflow. There is insufficient information to calculate the magnitude of this discharge and it is likely to be influenced by density effects at the seawater interface.
- Downward leakage to basement considered to be negligible.
- Groundwater in Tertiary Sand is believed to be under pressure and Tertiary Clay is considered to be a leaky aquitard. Hence upward leakage to Quaternary is possible, particularly in the region down gradient of cross section BB' in the Uley South lens area where an upward hydraulic gradient is observed.

Groundwater Flow and Aquifer Properties

- Properties likely to vary spatially due to fluvial nature of deposition.
- Only have one data point upon which to base estimates of properties (Uley South production well PT1: T = 682 m^2/d; S = 0.007).
- Estimate of groundwater residence time in the Tertiary Sand below Big Swamp is 3000–6500 yrs. This is an area of the Tertiary Sand aquifer receiving leakage from Big Swamp that may be thin or discontinuous.

Groundwater Salinity

- Groundwater salinities in the Tertiary Sand follow a similar pattern to those in the overlying Quaternary aquifer and have not changed significantly since the early drilling in the 1950s.
- High groundwater salinities (> 1000 mg/L) along the western half of the Uley East lens considered to be a result of leakage from Big Swamp.
- The cause of high groundwater salinities (1200–3300 mg/L) below the western portion of the Uley South lens is unknown, but this area is isolated from the rest of the Tertiary aquifer below the Uley South lens (Evans, 1997).

4.4.3 TERTIARY CLAY

The Upper Tertiary unit consists of a 5–25 m thick clayey laterite paleosol horizon. This Tertiary Clay forms an aquitard between the Tertiary Sand and the Quaternary aquifer systems, with a K_v estimated in the Uley South region to be 6.8 x 10^{-4} m/d (Morton & Steel, 1968). Again, due to the fluvial depositional environment of the Tertiary sediments, the Tertiary Clay is not expected to have spatially uniform hydraulic properties and is described by Morton and Steel (1970) as consisting of clays and silty clays.

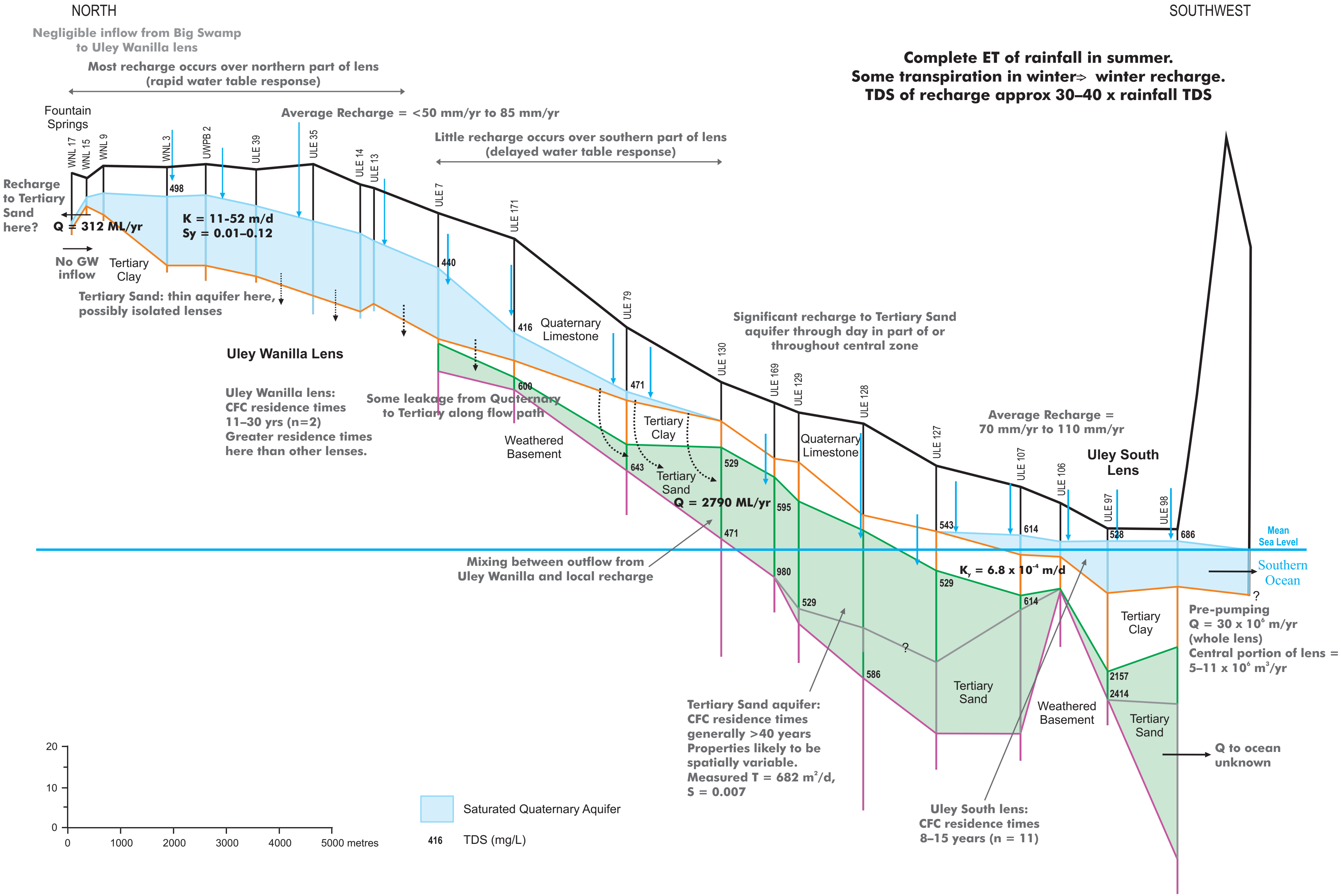

Figure 4.13. Summary of hydrogeological conceptual model shown on Cross Section HH'.

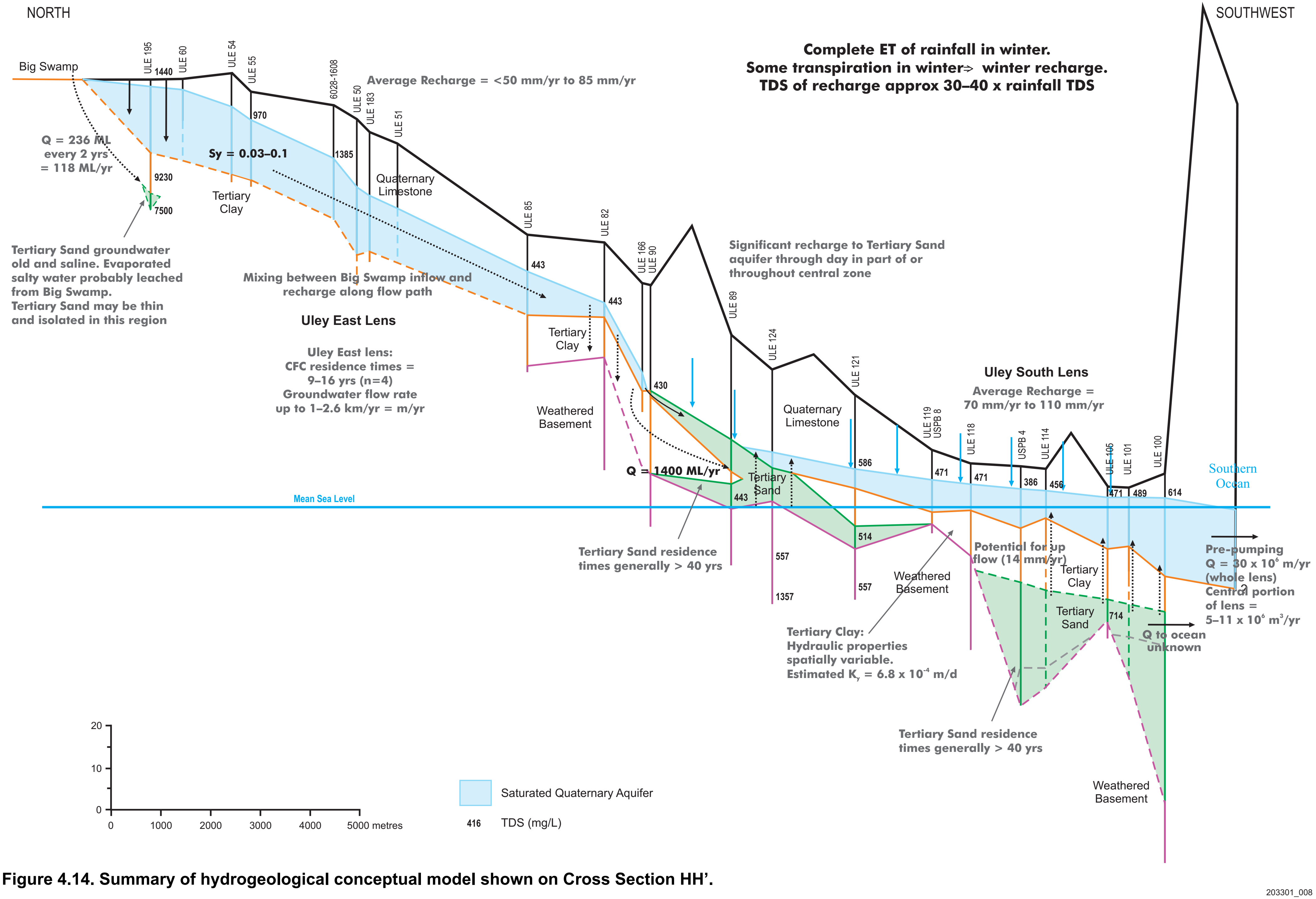

Figure 4.14. Summary of hydrogeological conceptual model shown on Cross Section HH'.

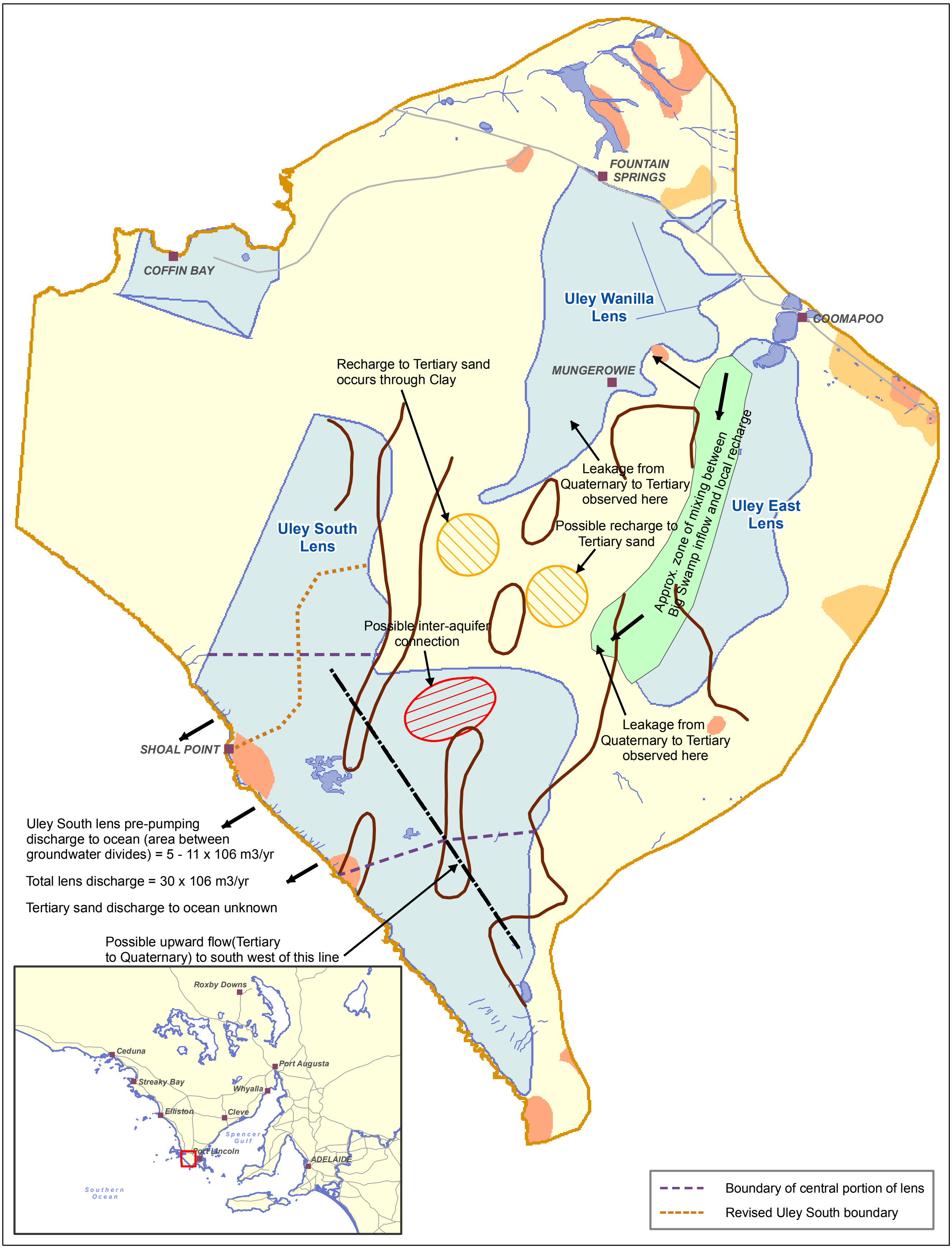

Figure 4.15. Spatial summary of hydrogeological conceptual model

Locality
Drainage
Road
Waterbody
Swamp
Uley Basin
Quaternary groundwater lens

Tertiary sand extent
Tertiary clay absent

Geology

Quaternary sediment
Tertiary sediment
Basement outcrop

N

0 1.25 2.5 5 km

Map Production: Resource Information Group
Department of Water, Land and Biodiversity Conservation

Map Projection: MGA Zone 53
Map Datum: GDA94.

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The clay is considered to be a relatively effective aquitard due to the fact that hydraulic heads in the underlying Tertiary Sand are generally above the base of the clay. However, Morton and Steel (1968) considered it to be a leaky aquitard and the lack of field information on the layer means that there may be a number of unidentified areas where effective connection between the Quaternary and Tertiary aquifers occurs through the clay.

The clay is not continuous across the entire study area, with a number of areas identified in which the Quaternary Limestone is in direct contact with the Tertiary Sand (Evans, 1997). Examples of such areas include the north western, south eastern and north eastern portions of the Uley South lens area (Map 1, App. A). In some other areas, Tertiary Clay has been identified, but its thickness is not known. These occur below the northern portion of the Uley Wanilla lens, below most of the Uley East lens and below the western part of the Uley South lens.

4.4.4 QUATERNARY LIMESTONE

The Quaternary Bridgewater Formation limestone forms a thin veneer over the basement controlled structure in the east and north-west of the study area and is over 130 m thick in the Uley South region. The unit consists of Aeolian sediments, fine sand-sized shell fragments that are generally either unconsolidated or loosely aggregated, deposited during the Pleistocene Ice Age. However, the occurrence of near-vertical cliffs at the Southern Ocean suggest that the Quaternary Limestone can be more consolidated in some parts. It is known to be laterally variable in composition, being marly and of a relatively low permeability in some areas and hard and cavernous in others, for example in the central Uley South lens area (Morton & Steel, 1970). The limestone is variable in thickness, with the maximum thickness occurring in the south-west trending troughs that were partially filled by the Tertiary units prior to deposition of the Quaternary sediments. Secondary porosity is known to occur within the unit, along with secondary cementation in the form of a calcrete horizon at the evaporation front.

Groundwater in the Quaternary limestone occurs as lenses, the Uley East, Uley Wanilla and Uley South lenses, forming water supplies with high yields and low salinity (< 700 mg/L). The freshwater lenses are conventionally delineated by the 1000 mg/L isohaline. However, for the purpose of this report, the groundwater lenses are referred to as the saturated portions of the Quaternary aquifer. The hydrogeologic and hydrochemical characteristics of each of the lenses are described in detail in following sections. It is known that the Uley Wanilla and Uley East lenses have been connected during periods of higher rainfall than today (S. Evans, pers. comm.), and earlier workers have considered the two as one lens, known as the Uley Wanilla lens (e.g. Morton & Steel, 1970; Barnett, 1978).

Hydrogeologically, the Quaternary limestone aquifer can be divided into two zones, the Uley Wanilla / Uley East Zone in the north of the study area and the Uley South Zone. These zones are separated by an area of high topographic elevation in which the Quaternary aquifer is dry or marginally saturated, and the water table is predominantly in the Tertiary or Basement units (App. A). The apparent lack of continuity between the northern lenses and the Uley South lens has led to the conclusions that (1) there is no groundwater flow from the Uley Wanilla / Uley East region into the Uley South lens and (2) outflow from the northern lenses must enter the underlying Tertiary Sand aquifer through gaps or relatively high permeability regions in the Tertiary Clay. Similarly, groundwater inflows to the Uley Basin Quaternary aquifers are considered to be negligible as the lenses have limited extents.

4.4.5 THE ULEY SOUTH GROUNDWATER LENS

4.4.5.1 General Characteristics

The Uley South lens occurs in a topographically closed basin. The central portion of the basin is relatively flat to undulating at an elevation of less than 20 m AHD. In this area, where the topography is lower than 5 m AHD, occasional flooding occurs when intense rainfall coincides with a high groundwater table in the Quaternary aquifer. The south-western boundary of the basin is formed by a set of coastal cliffs, with elevations greater than 140 m AHD, and the western, northern and eastern boundaries are all controlled by topographic highs that rise from 70–140 m AHD.

The western boundary of the Uley South lens was originally determined by Evans (1997) to lie within the sand dunes of the Coffin Bay National Park. However, subsequent review of observation well data has indicated that all wells in the north-western arm of the lens are dry and hence the boundary should be modified to reflect the reduced area of saturated Quaternary limestone, as shown on Map 1.

There is a good understanding of the geology down to the basement units throughout most of the Uley South region. The Uley South lens occurs in a north-east south-west trending basement trough system that have been infilled with Tertiary and Quaternary sediments. The Uley South production borefield is located within a broad shallow trough and is separated from the north-western and south-eastern sections of the lens by basement highs, which result in local groundwater divides in the Quaternary aquifer (Map 1).

4.4.5.2 Water Sources

Groundwater Inflow

The only inflow to the Uley South lens is believed to be local rainfall and surface runoff/ subsurface flow from topographically high regions of the surface drainage catchment (Evans, 1997). Earlier workers identified a possible hydraulic connection between the northern lenses and Uley South (e.g. Painter, 1969, Morton & Steel, 1970; Barnett, 1978). Barnett (1978) estimated a flow of 11 x 106 m3/y from the Uley Wanilla lens (then considered to incorporate both the Uley Wanilla and Uley East lenses) to the Uley South lens through a 5 km connection between the lenses. However, it is now considered that no contribution of that magnitude from the Uley Wanilla and Uley East lenses to Uley South lens is feasible (Scott Evans, pers. comm.). The Quaternary aquifer in the central portion of the study area has been observed to be dry (Evans, 1997).

The pattern of hydraulic gradients in the Tertiary aquifer is similar to that of the Quaternary in the Uley South region and Sibenaler (1976) suggested that the Quaternary and the Tertiary are connected in this region. The water levels are coincident in the north-eastern portion of the lens where the Tertiary Clay is absent, suggesting negligible vertical flow between the two aquifers in this region. Further along the flow path, however, the Tertiary Sand becomes confined and the standing water levels in wells in this aquifer marginally exceed those in Quaternary aquifer wells. As described in Section 4.4.2.3, this indicates a potential for upward flow from the Tertiary aquifer into the lens through the leaky Tertiary Clay aquitard.

The maximum observed hydraulic head difference in this area is 0.2 m. Based on an aquitard thickness of 10 m, a vertical hydraulic conductivity of 6.8 x 10-4 m/d and a porosity of 0.35, this results in an upward leakage of approximately 14 mm/y.

Rainfall Recharge

Morton and Steel (1970) observed that the topographic ridge to the north-east of the Uley South lens would contribute significant runoff to aquifer recharge. Likewise, Evans (1997) observed that overland flow from the internal boundary of the coastal cliffs occurs during high rainfall events. This flow travels over a distance of hundreds of metres before recharging through depressions and cavities (Figs 4.4 and 4.12).

Selby (1974) calculated, using Darcy's Law, that outflow from the Uley South lens to the ocean is approximately 50% of rainfall. Assuming the only inflow to the lens to be rainfall recharge and the only outflow to be discharge to the ocean, this implies an average annual recharge rate of the order of 220 mm/y. Barnett (1978) used a hydrograph method to estimate recharge to the Uley South lens. Winter rainfall was plotted against rise in water table to give a limiting winter rainfall for recharge to occur of 217 mm. Average winter rainfall was estimated to be 322 mm/y and, based on this, average winter recharge was estimated to be 105 mm (Table 4.1).

The limiting winter rainfall method of Barnett (1978) could now be refined to include rainfall and water level change data obtained since the 1978 study, provided that hydrographs can be shown to be unaffected by groundwater extraction. The limitation of this method is that it relies upon a linear relationship between change in groundwater level and winter rainfall. As in any natural system, particularly one with such heterogeneity as the Uley Basin, the data is most likely to be broadly scattered around a linear trend. Hence a significant degree of uncertainty and averaging is inherent in the derivation of a linear relationship.

Evans (1997) estimated average annual rainfall recharge using a range of different methods, as described in Section 4.3. These estimates, along with those of earlier authors, are shown in Table 4.1. Early recharge estimates (e.g. Morton & Steel, 1968; Sibenaler, 1976) were based on water balances calculated using conservative values of aquifer transmissivity. The hydrograph method of Barnett (1978) uses an empirical relationship between groundwater level fluctuation and winter rainfall (see Section 4.3), a method that is independent of knowledge of aquifer properties and may provide a good first estimate of recharge. The general agreement between this and the estimates made by Evans (1997), using the chloride mass balance and water balance (with seawater interface consideration) methods, provides confidence in an average annual recharge rate between 70 mm/y and 110 mm/y for the lens. The low value of 46 mm/y estimated using the water level hydrograph method is likely to be due to extreme difficulties in estimating specific yields for the heterogeneous aquifer, and the lack of resolution of water level peaks by the monthly water level monitoring program (Evans, 1997).

The CFC method used by Evans (1997) demonstrates great potential for providing point estimates of recharge rates. However, the long screens of many of the observation wells sampled mean that the actual depth of the sample cannot be determined, and extremely large uncertainties (up to 225 mm/y for some wells) need to be considered in the recharge estimates (see Section 4.3.1). Despite this, it can be said that the data shows a large amount of spatial variability in recharge rates for the Uley South lens, with data from some shallow wells (screens < 7 m below the water table) indicating recharge rates less than 80 mm/y. One deeper well (screen ~9–11.5 m below the water table) demonstrates a recharge rate greater than 200 mm/y. Other wells, with screen intervals of 12 m may be sampling water from anywhere within this interval and hence can only be relied upon to provide recharge rates somewhere between 25–250 mm/y. The spatial distribution of recharge rates estimated by Evans (1997) using CFC concentrations is shown on Map 4.

4.4.5.3 Water Outflows

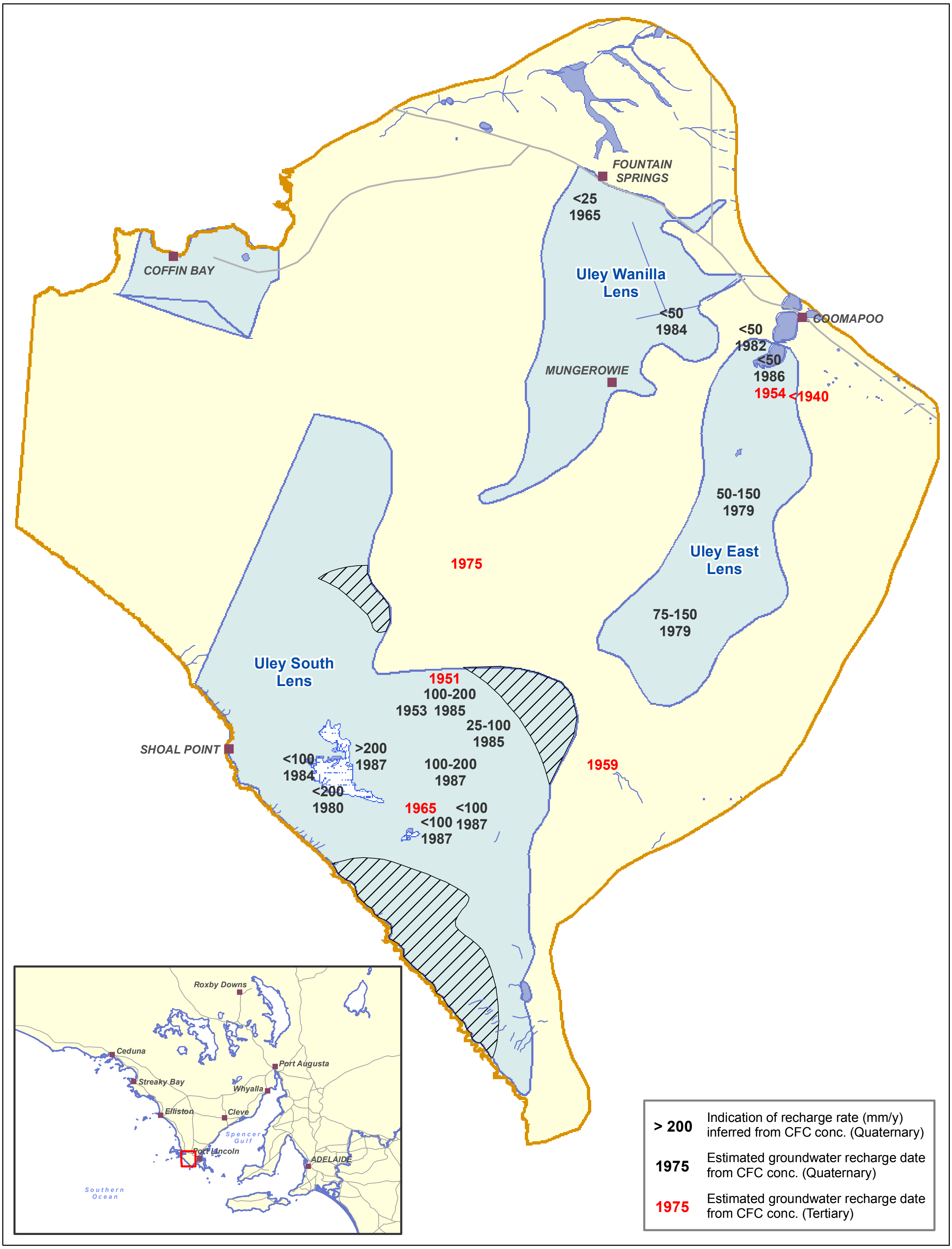
Natural outflow from the Uley South lens is via groundwater discharge to the ocean. Morton and Steel (1970) describe the occurrence of springs at Shoal Point, among other locations, at the contact between the Quaternary sediments and the basement structure. As described above, Selby (1974) calculated, using Darcy's Law, that the basin outflow to the ocean is approximately 50% of rainfall. Sibenaler (1976) used what is now considered to be a conservative transmissivity value of 0.1 x 10^4 m^2/d to estimate a basin outflow of 4.2 x 10^6 m^3/y. Barnett (1978) revised this estimate based on a transmissivity of 0.5 x 10^4 m^2/d to 30 x 10^6 m^3/y. Evans (1997) estimated a pre-pumping groundwater discharge from the section of the lens between the two no-flow boundaries shown in Map 2 of 10.7 x 10^6 m^3/y, also using a simple Darcy's Law calculation. Application of the Ghyben-Herzberg principle for discharge at the seawater interface revised this to 5.3 x 10^6 m^3/y.

Groundwater extractions exceeding 4000 ML/yr commenced in 1976. There were 8 production bores extracting between 3000–6000 ML/yr from the Uley South lens to 1996 and there are currently 17 production wells extracting ~7200 ML/y. Groundwater levels in the lens remained constant until 1985 and then began decreased for a short period, apparently in response to a decline in annual rainfall rather than groundwater extraction (Evans, 1997).

Evaporation of ponded water and evapotranspiration of shallow groundwater is expected to occur from the approximately 0.85 km^2 area of swampy land, just inland of the coastal cliffs in the central Uley South region (Map 1). This area has been observed to be inundated during periods of extreme rainfall and the depth to groundwater has been observed at between one and three metres (Evans, 1997). Evaporation of ponded surface water is minimised by the fact that inundation occurs rarely (approximately once in twenty five years) and probably occurs during the winter period when potential evaporation is lowest. Low groundwater chloride concentrations in the Quaternary aquifer in this area support the hypothesis that evapotranspiration from the swampy region is negligible. Monitoring of groundwater chloride / salinities around this area would be useful to confirm that this is the case throughout the year.

4.4.5.4 Groundwater Flow

Groundwater equipotentials for the Uley South lens are shown on Map 1. Groundwater flow is generally from the north-east to the south-west. Two basement highs cause the central groundwater flow system in which the Uley South production borefield is located to be isolated from the north western and south eastern portions of the lens (Map 1). A karstic region, indicated by high groundwater flow rates, occurs in the central portion of the lens (Sibenaler, 1976).



Map 4. Groundwater recharge dates and recharge rates inferred from CFC data for the Quaternary lenses and Tertiary sediments

- Locality
- Drainage
- Road
- Waterbody
- Swamp
- Uley Basin
- Quaternary groundwater lens
- Tertiary clay absent

N

0 1.25 2.5 5 km

Map Production: Resource Information Group
Department of Water, Land and Biodiversity Conservation

Map Projection: MGA Zone 53
Map Datum: GDA94.

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4.4.5.5 Aquifer Properties

Estimates of Quaternary aquifer transmissivities in the Uley South region are an order of magnitude greater than in the Uley Wanilla region and highly variable, ranging between 680–13 000 m^2/day. Map 5 shows some inferred hydraulic conductivities. The high transmissivities result in a low hydraulic gradient across the lens. Specific yields for Uley South were estimated using water table recovery curves by Evans (1997) to range between 0.03–0.17. Painter (1969) observed well yields of up to 71 L/s, but found pump test results to be highly variable and not reliable in estimating Quaternary aquifer properties.

4.4.5.6 Groundwater Salinity

Groundwater salinities (TDS) observed during the initial drilling programs are discussed by Evans (1997). Groundwater in the Uley South Quaternary groundwater lens generally had salinities less than 600 mg/L at that time. Discrete zones with salinities less than 500 mg/L were identified in the central lens area, as well as in the isolated south eastern portion of the lens and along the north eastern edge of the isolated north western portion of the lens. These lower groundwater salinities are likely to be due to enhanced recharge (reduced evapotranspiration) in these regions. The salinity distribution did not change significantly for the 1993/1994 sampling event reported by Evans (1997), suggesting that groundwater extraction had not had a noticeable effect on groundwater salinities in this lens.

4.4.5.7 Summary of Uley South Lens Conceptual Model

The details of the conceptual model for the Uley South groundwater lens are summarised on Figures 4.13–4.15.

General Characteristics

- The Uley South lens occurs in a topographically closed basin.
- Groundwater occurs in a series of north east south west trending basement troughs.
- The low topographic surface near the centre of the basin often floods during heavy rainfall resulting in a swampy area, as shown on Map 1.

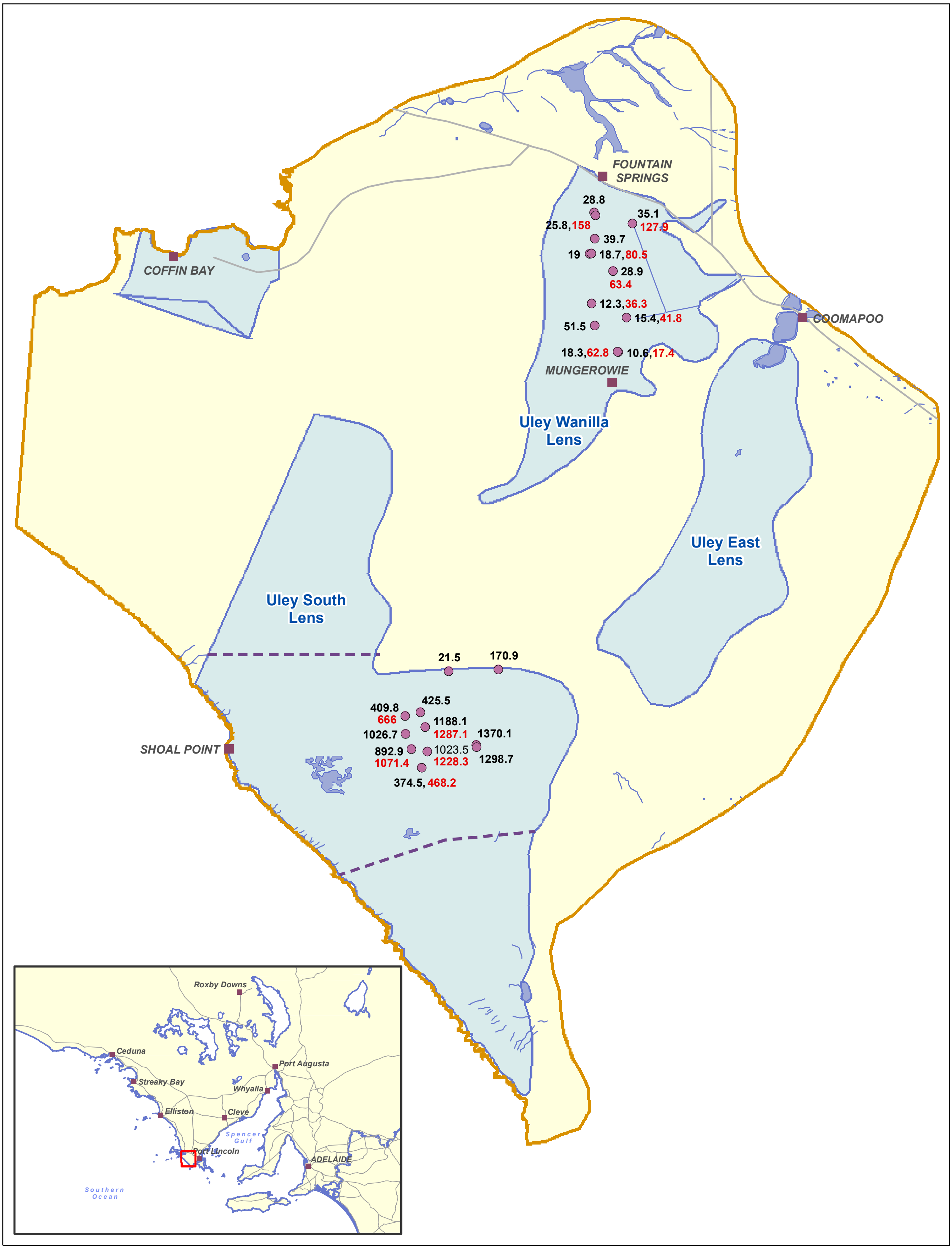
Water Sources

Groundwater Inflow:

- Only inflow is believed to be local rainfall and surface runoff / subsurface flow from topographically high regions of the catchment.
- It is currently considered that there is no groundwater inflow from the Uley Wanilla and Uley East lenses due to the observation that the Quaternary aquifer between these and the Uley South lens is dry.
- Upward hydraulic gradients occurring to the south west of cross section BB' suggest the possibility of upward flow from the Tertiary Sand in this region (up to 14 mm/y).

Rainfall Recharge

- The topographic ridge to the north east of the basin and the internal boundary of the coastal cliffs are likely to contribute large amounts of runoff to recharge the groundwater lens.
- Recharge estimates to date:



Map 5. Available hydraulic conductivity data (after Evans, 1997)

Locality
Drainage
Road
Waterbody
Swamp
Uley Basin
Quaternary groundwater lens
426 min
666 max
Quaternary aquifer hydraulic conductivity (m/d)
Boundary of central portion of Uley South lens

N
0 1.25 2.5 5 km

Map Production: Resource Information Group
Department of Water, Land and Biodiversity Conservation

Map Projection: MGA Zone 53
Map Datum: GDA94.

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j4412_mxd/Map5.mxd 31 August 2006 JT

- Selby (1974): R = 220 mm/y (50% of rainfall)
- Barnett (1978): Limiting winter rainfall = 217 mm, ⇒ average R = 105 mm/y
- Evans (1997): Chloride mass balance and basin water balance ⇒ R = 70–110 mm/y.
- CFC method shows good potential for providing point estimates of recharge, providing discrete sampling intervals can be assumed.
- CFC method provided point estimates of recharge ranging between < 80 mm/y and > 200 mm/y (see Map 4).

Water Outflows

- Main outflow is discharge to the ocean. Barnett (1978) estimates this to be approximately 30 x 10^6 ML/y. Evans (1997) estimates discharge for the central portion of the lens, shown on Map 1, to be between 5 x 10^6 ML/y and 11 x 10^6 ML/y.
- The Uley South production borefield consists of 17 bores, currently extracting ~7200 ML/y. Extractions exceeding 4000 ML/y commenced in 1976.
- Evapotranspiration from the swampy area in the centre of the basin is unknown, but considered to be negligible based on the fact that inundation occurs during winter and that there is no significant increase in groundwater [Cl^-] in this region.

Groundwater Flow and Aquifer Properties

- Groundwater flows from the north east to the south west.
- The Uley South production borefield occurs within the central portion of the lens and is separated from the other two by these basement highs.
- Aquifer transmissivities are high and variable, with a measured range between 680–13 000 m^2/day.
- Specific yields range between 0.03 and 0.17.

Groundwater Salinity

- Quaternary aquifer groundwater salinities are generally less than 600 mg/L, with some areas of low salinity (<500 mg/L) potentially indicating regions of high enhanced recharge (low evapotranspiration).
- The pattern of groundwater salinities has not changed significantly since the initial drilling in the 1950s, suggesting little effect from groundwater pumping.

4.4.5.8 Water Balance of the Uley South Lens

A simple water balance for the Uley South lens, based on the conceptual model described above and shown in Figures 4.13–4.15, was constructed and is presented in Appendix C. This water balance was calculated for the central portion of the lens, as shown on Map 1, which is developed by the Uley South production bore field. As the chloride mass balance is considered to provide a good estimate of average annual rainfall recharge across the groundwater lenses, the estimate from this method of 70 mm/y was used in the water balance calculation. The rainfall catchment area was considered to be the same as the area of the central portion.

The discrepancy in the water balance of 170 ML/y was considered to be small compared with the magnitudes of the main components, suggesting that it is a reasonable representation of the real system. Although upward leakage from the Tertiary aquifer possibly occurs in the region to the south west of cross section BB', the magnitude of this (~350 ML/y) is small compared with the main inflow (rainfall recharge = 4760 ML/y) and outflow (outflow to the southern ocean = 5280 ML/y).

4.4.6 THE ULEY WANILLA LENS

4.4.6.1 General Characteristics

The Uley Wanilla Lens rises from 70 m AHD in the south-west to a flat to undulating plateau at approximately 100 m AHD. Its boundaries are formed by basement highs in the west and east, causing the Quaternary aquifer to become unsaturated here, and the extent of the Quaternary aquifer in the north. It is believed that the southern boundary of the lens is formed by downward leakage of groundwater from the Quaternary aquifer to the underlying Tertiary Sand.

4.4.6.2 Water Sources

4.4.6.2.1 Groundwater and Surface Water Inflows

Lateral groundwater inflows to the Uley Wanilla lens are considered to be negligible as there is no physical extension of the lens outside the Uley Basin, and the Tertiary Clay, with which the northern boundary of the lens is in contact, is not expected to contribute much inflow due to its low permeability (Evans, 1997). However, an anomaly in groundwater salinity occurs at the north eastern boundary of the Uley Wanilla lens may suggest some inflow from a saline water source, as described further in Section 4.4.6.6. Groundwater in the Uley Wanilla lens flows to the south west away from Big Swamp, which is a topographic high. Although a surface water drainage connection exists between Big Swamp and the Uley Wanilla lens, it is considered that the recharge contribution from Big Swamp is negligible, with surface inflow to the lens occurring through a narrow interface only once in every 10–15 years (Evans, 1997).

4.4.6.2.2 Rainfall Recharge

Rainfall recharge to the Uley Wanilla lens was estimated using the chloride mass balance approach by Evans (1997) to be 51 mm/y, and a water balance analysis yielded a recharge rate of 85 mm/y (Table 4.1). As described in Section 4.3.1, the recharge estimate of 20 mm/y from the water table fluctuation method is likely to be an under estimate. Two CFC data points from the northern part of the lens suggest recharge rates less than 50 mm/y (Table 4.1; Map 4). More CFC data points would be required to further assess the spatial variability in rainfall recharge across the Uley Wanilla lens. Based on the studies carried out to date, a reasonable range for average annual rainfall recharge to the Uley Wanilla lens is from <50–~85 mm/y. A limiting winter rainfall method similar to that of Barnett (1978) could be applied to the Uley Wanilla lens for comparison with these other estimates, provided that sufficient groundwater hydrograph records exist to determine the magnitude of the limiting winter rainfall.

Evans (1997) suggests that the area contributing recharge to the Uley Wanilla lens can be defined as the area of saturated limestone where a rapid water table response to intense rainfall events is observed. This occurs in the north of the lens and is estimated to be ~36.5 x 10^6 m^2 in area. A delayed response to rainfall is observed in the south of the Uley Wanilla lens and this is proposed by Evans (1997) to be due to very little recharge in this area, but lateral flow of the pressure front along the groundwater flow path. It may also be that lower recharge rates occurring in this region result in a delayed water table response.

$\delta^{13}C$ data from the Quaternary aquifer supports the hypothesis that "enhanced recharge" is not widespread across this groundwater lens. The $\delta^{13}C$ values of the groundwater samples from this lens are all greater than –6 ‰, suggesting dissolution of carbonate aquifer matrix (relatively long residence times) and little influence of enhanced recharge (Fig. 4.11; Map 2).

4.4.6.3 Water Outflows

The natural southerly outflow from the Uley Wanilla lens is believed to be via downward leakage through the Tertiary aquitard near the southern limits of the lens. Here, the Quaternary limestone becomes unsaturated and the groundwater chemistry in the Tertiary aquifer is similar to that in the upgradient Quaternary aquifer. A natural discharge from the Uley Wanilla lens also occurs at Fountain Springs in the north, where groundwater historically discharged to the land surface and has now been fully captured and extracted through nine water supply pumps and a trench with two sump pumps since the 1960s. Pre-pumping groundwater discharge from the Uley Wanilla lens, at both the Fountain Springs discharge points and at the southern boundary of the lens, was estimated by Evans (1997) using Darcy's Law to be 310 ML/y.

Groundwater production from the Uley Wanilla lens began in 1949, ranging between ~300–2800 ML/y. Soon after this, water levels fell at a rate greater than those in the Uley East lens, and below the bases of observation wells. The difference in water levels between the two lenses increased when extraction exceeded 1500 ML/y.

4.4.6.4 Groundwater Flow

Groundwater in the Uley Wanilla lens flows along an initially gradual and then a steep hydraulic gradient towards the south west. This change in gradient is due to high transmissivities in the recharge area and low transmissivities or an increased aquifer slope to the south (Evans, 1997). The water table ranges from 103–40 m AHD across the lens. More evolved carbon isotope signatures, indicating more influence of carbonate aquifer dissolution in the Uley Wanilla lens, suggest greater groundwater residence times and hence slower groundwater flow rates in this lens than in the other two lenses (Fig. 4.11). This is supported by higher residence times (11–30 yrs; n=2) estimated using CFC data (Evans, 1997) and is also discussed below in relation to observed groundwater TDS values. The greater apparent groundwater residence times in this lens may also be a result of the high level of groundwater extraction from the bore field, which possibly extracts the shallower, more recently recharged groundwater.

Both the Uley Wanilla and Uley East lenses exhibited decreasing water levels prior to the 1960s, but this was steeper in the Uley Wanilla lens. Subsequent to this, whilst the water levels in the Uley East lens recovered in response to higher rainfall, this recovery was not observed in the Uley Wanilla lens due to the operation of the production bore field there.

4.4.6.5 Aquifer Properties

Estimated hydraulic conductivities for the Uley Wanilla lens range between 11–52 m/d. Specific yields for the Uley Wanilla lens were estimated using water table recovery curves by Evans (1997) to range between 0.01–0.12.

4.4.6.6 Groundwater Salinity

During the initial 1930s–60s drilling programs, groundwater TDS across the Uley Wanilla lens was below 1000 mg/L, with a zone in the centre of the lens having TDS values >500 mg/L (600–700 mg/L). The 1993–94 sampling program of Evans (1997) showed that this zone of higher TDS had increased in size slightly. Despite the higher TDS of groundwaters in this central zone, chloride concentrations ($[Cl^-]$) are still generally below 200 mg/L (Map 2) and a large portion of the total dissolved solids is alkalinity derived from carbonate mineral dissolution (see alkalinity graph on Fig. 4.9b). The high groundwater alkalinities are consistent with the positive (> -6 ‰) $\delta^{13}C$ signatures (Map 2), which are also caused by dissolution of carbonate minerals. Greater dissolution of the carbonate aquifer matrix indicates relatively long groundwater residence times (and hence slower groundwater flow rates) compared with the other two lenses. As described above, the greater apparent groundwater residence times in the central portion of this lens may also be a result of the high level of groundwater extraction from the bore field, which possibly extracts the shallower, more recently recharged groundwater.

The expansion of the high TDS zone from a small area to most of the northern part of the Uley Wanilla lens, between the initial drilling programs and the 1993–94 sampling, suggests an expansion of this slow groundwater flow zone during this time period. This may be due to a reduction in groundwater recharge between these two sampling events, affecting the hydraulic gradient across the lens, reflecting the dynamic nature of the system, or an increase in groundwater extraction from the bore field.

One observation well at the north eastern boundary of the Uley Wanilla lens intersects groundwater with a chloride concentration >1000 mg/L (Map 2). This would initially suggest inflow from an evaporated surface water body similar to Big Swamp. However, unlike the evaporated stable isotope signatures of Quaternary groundwaters sampled down-gradient from Big Swamp ($\delta^{18}O$ = -2.79 ‰, $\delta^{2}H$ = -15.8 ‰), the signature of this sample from the Uley Wanilla lens is similar to that of local rainfall ($\delta^{18}O$ = -4.17 ‰, $\delta^{2}H$ = -23.5 ‰) (Fig. 4.7). This suggests that evaporation is not the primary source of the salinity observed in the north east of the Uley Wanilla lens. However, re-dissolution by rainfall of previously deposited salts, where, for example, a lake has evaporated to dryness, is a possibility. In addition, the chemical composition of the high $[Cl^-]$ Uley Wanilla groundwater is slightly different from that at the southern extent of Big Swamp in the Uley East lens. The former has higher Ca^{2+} and alkalinity concentrations, plotting above the main trends on Figure 4.9a and suggesting a greater residence time in the aquifer (more influence of carbonate mineral dissolution) than the groundwater influenced by Big Swamp.

4.4.6.7 Summary of Uley Wanilla Lens Conceptual Model

The details of the conceptual model for the Uley Wanilla groundwater lens are summarised on Figures 4.13 and 4.15.

General Characteristics

- The lens is bounded by basement highs in the west and east and by the saturated extent of the Quaternary aquifer in the north.
- The southern boundary, where the limestone aquifer becomes dry, is believed to be caused by groundwater leakage from the Quaternary aquifer into the Tertiary aquifer.

Water Sources

Groundwater and Surface Water Inflow:

- Groundwater inflows are considered to be negligible.
- There is a connection to Big Swamp, but inflows from this source are considered to be negligible, occurring every 10–15 yrs.
- There is a possible, but insignificant, inflow from a saline source to the north eastern corner of the lens.

Rainfall Recharge:

- Average annual rainfall recharge is estimated to range between less than 50–85 mm/y.
- Most rainfall recharge is considered to occur in the northern portion of the lens.
- The occurrence of lower recharge rates across the Uley Wanilla Lens than across the Uley South lens is supported by $\delta^{13}C$ values that are greater than –6 ‰.
- A limiting winter rainfall method similar to that of Barnett (1978) could be applied to the Uley Wanilla lens for comparison with the other estimates and to provide temporal estimates of rainfall recharge.

Water Outflows

- Leakage of groundwater from the Quaternary to the Tertiary aquifer at the southern extent of the Uley Wanilla lens is supported by similar groundwater salinities ([Cl^-], $\delta^{13}C$ values and major ion compositions between the two aquifers at this location.
- Total groundwater outflow from the lens at Fountain Springs and the south western boundary is estimated to be 310 ML/y.
- Groundwater production commenced in 1949, ranging between ~300–2800 ML/y.

Groundwater Flow and Aquifer Properties

- Groundwater flows generally towards the south west.
- A change in hydraulic gradient along the flow path from gradual to steep is considered to be due to a combination of lower aquifer transmissivities and a more sloping aquifer in the south of the lens.
- Comparatively more evolved carbon isotope signatures suggest longer groundwater residence times (and hence slower groundwater flow rates) than in the other two lenses.
- This may also be due to the high level of groundwater extraction from the bore field in this lens, which possibly extracts the shallower, more recently recharged groundwater.
- Estimated hydraulic conductivities for the Uley Wanilla lens range between 11–52 m/d.
- Specific yields are estimated to range between 0.01–0.12 (Evans, 1997).

Groundwater Salinity

- A zone of higher TDS (600–700 mg/L) occurs in the centre of the lens. This is caused by higher groundwater alkalinities resulting from slower groundwater flow rates.
- Again, this may also be due to extraction of shallower, recently recharged groundwater from the bore field in this region.
- Salinity differences observed between the early and recent sampling programs may be due to sampling during years of vastly different recharge.

- There appears to be a climatic control over groundwater salinity, with higher salinities occurring during low recharge years and lower salinities occurring during high recharge years.
- A high [Cl^-] in the Quaternary aquifer in the north east corner of the lens suggests input of saline water from somewhere, with the high [Cl^-] possibly caused by dissolution of evaporite minerals in a lake bed.

4.4.6.8 Water Balance of the Uley Wanilla Lens

A simple water balance for the Uley Wanilla lens, based on the conceptual model described above and shown in Figures 4.13 and 4.15, was constructed and is presented in Appendix C. Since the chloride mass balance is considered to provide a good estimate of average annual rainfall recharge across the groundwater lenses, the estimate from this method of 50 mm/y was used in the water balance calculation (Evans, 1997). In using the rainfall recharge estimate from the chloride mass balance method in the water balance calculations, the entire rainfall catchment area (55.7×10^6 m^2) must be used to estimate the total recharge to the lens.

The discrepancy in the water balance of 317 ML/y was considered to be small compared with the magnitudes of the main components, suggesting that it is a reasonable representation of the real system. However, if the discrepancy was to be attributed to downward leakage to the Tertiary Sand aquifer, when applied across the whole lens area, this results in a leakage of 8 mm/y.

4.4.7 THE ULEY EAST LENS

4.4.7.1 General Characteristics

The topography of the Uley East lens rises from 60 m AHD in the south and plateaus at ~105 m AHD to the south of Big Swamp. Its boundaries are formed by basement highs in the west and east causing the Quaternary aquifer to become unsaturated here, and the extent of the Quaternary aquifer in the north. It is believed that the southern boundary of the lens is formed by downward leakage of groundwater from the Quaternary aquifer to the underlying Tertiary Sand.

4.4.7.2 Water Sources

4.4.7.2.1 Groundwater and Surface Water Inflows

Groundwater inflows to the Uley East lens are considered to be negligible as there is no physical extension of the lens outside the Uley Basin, and the Tertiary Clay, with which the northern boundary of the lens is in contact, is not expected to contribute much inflow due to its low permeability (Evans, 1997). Similarly to the Uley Wanilla lens, groundwater in the Uley East lens flows to the south west away from Big Swamp, which is a topographic high. It is considered that Big Swamp regularly contributes recharge to the Uley East lens (Evans, 1997). Recharge from Big Swamp only occurs when the third basin fills. Measurements of the free water line in the third basin between 1941–56 showed that the this portion of Big Swamp filled on average every second year. During these proposed recharge events, adjacent Quaternary aquifer monitoring bores showed sharp rises in water table by up to 5.7 m. Monitoring records from these bores that extend from 1941 until present day have shown that recharge occurred in 44% of the years during that period (Evans, 1997). Measurements of surface inflows in the Big Swamp have led to an estimate for groundwater recharge of 236 ML every second year (Evans, 1997).

The inflow from Big Swamp is supported by the salinity ([Cl^-]) and carbon isotope signature of Quaternary aquifer groundwater from the piezometer nest at the southern boundary of Big Swamp (Map 2). The groundwater [Cl^-] of 463 mg/L measured in April 1994 is considerably higher than that of most other Quaternary groundwaters in the Uley Basin. A relatively negative $\delta^{13}C$ signature of –11.5 ‰ (as well as a high ^{14}C content of 85.8 pmC) is consistent with local enhanced recharge and a short groundwater flow path (i.e. little time for dissolution of the carbonate aquifer matrix). Additionally, the extremely positive stable isotope signature of the Quaternary groundwater at the southern margin of Big Swamp (δ^2H = -15.8 ‰; $\delta^{18}O$ = -2.79 ‰) compared with the average value for Quaternary aquifer groundwaters ($\delta^2H \approx$ -25 ‰; $\delta^{18}O \approx$ -4.5 ‰; Fig. 4.7) indicates that the high salinity of this groundwater is primarily due to the process of evaporation (i.e. most likely in Big Swamp). The regularity of recharge from Big Swamp and hence its importance in the water balance of the groundwater lens is indicated by the fact that all groundwater along the flow path to the south west of Big Swamp has a high [Cl^-], low $\delta^{13}C$ ($\delta^{13}C$ = -10 ‰ to – 6 ‰) signature (Map 2). Additionally, groundwater from observation well ULE183, located approximately half way along this flow path, has an evaporated stable isotope signature ($\delta^2H \approx$ -20.8 ‰; $\delta^{18}O \approx$ -4.25 ‰) compared with the average for the Quaternary aquifer given above. It is likely that these intermediate signatures are due to mixing between groundwater flowing down gradient from Big Swamp and small amounts of local rainfall recharge. It is anticipated that the three sets of geochemical signatures described above could be used to calculate percentage contributions of groundwater throughflow from Big Swamp and rainfall recharge at a series of points along the flow path, and that this mixing fraction could be used as a calibration parameter for a numerical model.

4.4.7.2.2 Rainfall Recharge

The chloride mass balance method could not be used by Evans (1997) to estimate an average annual rainfall recharge for the Uley East lens due to the additional input of high salinity water from Big Swamp. However, a water balance analysis yielded an average annual recharge rate of 76 mm/y and groundwater CFC concentrations measured in the Quaternary aquifer suggest recharge rates ranging between <50 mm/y and up to 150 mm/y (Map 4). The lowest rainfall recharge rates (<50 mm/y) estimated from groundwater CFC concentrations occur around Big Swamp.

The yellow area on Map 2 indicates the area of the Uley East lens that appears to be affected by groundwater throughflow from Big Swamp. Much lower groundwater salinities occur along the eastern and south eastern edge of the Uley East lens indicating less influence from Big Swamp here. Application of the chloride mass balance approach to this zone of the lens only (average [Cl^-] = 93 mg/L; n = 3) yields a recharge rate of 49 mm/y for this eastern / south eastern margin of the lens (see App. C for calculations). This estimate is relatively consistent with the result of the water balance analysis (Table 4.2) and is at the lower end of the range of estimates from groundwater CFC concentrations (Table 4.2; Map 4), both of which were applied to the northern and western parts of the lens (Evans, 1997).

4.4.7.3 Water Outflows

Similarly to the Uley Wanilla lens, the natural outflow from the Uley East lens is believed to be via downward leakage through the Tertiary Clay aquitard near the southern limits of the lens. Here, the Quaternary limestone is unsaturated and groundwater chemistry in the Tertiary observation well ULE164 is observed to be similar to that in the upgradient Quaternary aquifer (Fig. 4.9b). The slightly enriched stable isotope signature of groundwater sampled from observation well ULE164 (δ^2H = -20.8 ‰; $\delta^{18}O$ = -3.39 ‰), compared with an average Tertiary groundwater signature of δ^2H = -25.5 ‰ and $\delta^{18}O$ = -4.52 ‰, is also consistent with mixing with evaporated water moving down through the Quaternary aquifer from Big Swamp. Groundwater discharge from the Uley East lens to the Tertiary aquifer was estimated by Evans (1997) using Darcy's Law to be 1400 ML/y.

4.4.7.4 Groundwater Flow

Similarly to the Uley Wanilla lens, groundwater in the Uley East lens flows towards the south west. The water table elevation ranges between ~100–30 m AHD across the lens. Water levels reflect the trends of the cumulative deviation of mean monthly rainfall at the Big Swamp rainfall station (Evans, 1997).

CFC data indicate an apparent increase in groundwater residence time along the groundwater flow path, consistent with a travel time of 3–8 years between the southern extent of Big Swamp and observation well ULE86 (distance of ~8 km). This results in an estimated groundwater flow rate of 1–2.6 km/y although the occurrence of continuous recharge along the flow path may cause an under estimate of groundwater residence times and hence an over estimate of groundwater flow rates.

The $\delta^{13}C$ signatures of groundwater in the Uley East lens range between -12.9‰ and -8.7‰. The trend along a flow path is for an initial decrease in ^{14}C with an increase in $\delta^{13}C$, followed by an increase in ^{14}C combined with a decrease in $\delta^{13}C$. This suggests that the predominant process affecting carbon isotopes is initially the dissolution of carbonate minerals and then the addition of modern recharge. This does not rule out the possibility of modern recharge occurring near the beginning of the flow path, but suggests that the effect of this process is small compared with the effect of carbonate mineral dissolution.

4.4.7.5 Aquifer Properties

Specific yields for the Uley East lens were estimated using water table recovery curves by Evans (1997) to range between 0.03–0.1. The observation wells on which these analyses were carried out are located in the northern half or the lens, along its central axis. There is currently no Quaternary aquifer transmissivity data available for the Uley east lens.

4.4.7.6 Groundwater Salinity

Quaternary aquifer groundwater salinity maps from the Uley East lens presented by Evans (1997), for both the initial drilling programs (1930s–60s) and the 1993–94 sampling program, show a plume of comparatively high salinity groundwater (TDS = 600–900 mg/L) occurring along the western half of the lens. Groundwater in the eastern half of the lens has low salinities considered to be typical of areas of enhanced recharge (TDS = 300–450 mg/L). As described above, the evaporated stable isotope signature of groundwater sampled approximately half way along the saline groundwater plume suggests that the source of this salinity is leakage from Big Swamp, which then mixes with rainfall recharge along the flow path.

The distribution of salinity in the Quaternary aquifer does not appear to have changed greatly between the 1930s–60s drilling program and the 199–94 sampling program. However, all salinities may have increased by approximately 200–400 mg/L. This increase is difficult to quantify due to the fact that different wells were sampled during the two programs. These differences may also be due to sampling at different times of the year and seasonal fluctuations similar to those observed in the Uley Wanilla and Uley South borefields.

4.4.7.7 Summary of Uley East Lens Conceptual Model

The details of the conceptual model for the Uley East groundwater lens are summarised on Figures 4.14 and 4.15.

General Characteristics

- Boundaries of the lens are formed by basement highs in the west and east and by the extent of the Quaternary aquifer in the north.
- The southern boundary is believed to be caused by downward leakage of groundwater from the Quaternary aquifer into the Tertiary Sand.

Water Sources

Groundwater and Surface Water Inflow

- Groundwater inflows considered to be negligible.
- Tertiary Clay not expected to contribute much inflow to Quaternary aquifer at northern boundary due to low permeability.
- Big Swamp is considered to regularly contribute recharge to the Uley East lens at approximately 240 ML every second year.
- The importance of Big Swamp in the water balance for the lens is suggested by an apparent salinity impact from the wetland along the entire length of the groundwater flow path.

Rainfall Recharge

- Estimates by Evans (1997) yielded average annual rainfall recharge values ranging from less than 50 mm/y to 150 mm/y. The higher value is a result of uncertainty in the depth of extraction of CFC samples from some wells.
- An average annual recharge rate estimate of 76 mm/y was obtained using a water balance method (Evans, 1997).
- Use of the chloride mass balance method for estimating an average annual recharge rate for the whole lens is inhibited by the input of high salinity water from Big Swamp. However, assuming that groundwaters in the eastern half of the lens are unaffected by this, a recharge rate of 49 mm/y was obtained for this region alone using the chloride mass balance method.
- Groundwater salinities and carbon isotope data reflect the influence of recharge along the entire groundwater flow path in the western half of the lens.

Water Outflows

- The natural outflow from the Uley East lens is believed to be via downward leakage through the Tertiary Clay aquitard near the southern extent of the lens.
- This is supported by groundwater chemistry and isotope data.

- Leakage is estimated at 1400 ML/y.

Groundwater Flow and Aquifer Properties

- Groundwater flows generally towards the south west.
- Groundwater levels reflect monthly rainfall patterns.
- An upper estimate of groundwater flow rate in the north eastern portion of the lens based on CFC data is from 1–2.6 km/y.
- Specific yields estimated to be between 0.03–0.1 (Evans, 1997).
- There is currently no aquifer transmissivity data available for the Uley east lens.

Groundwater Salinity

- Inflow of evaporated water from Big Swamp causes a plume of comparatively high salinity groundwater (TDS ~600–900 mg/L) in the Quaternary aquifer along the western half of the lens.
- Groundwater in the eastern half of the lens has low salinities considered to be typical of areas of enhanced recharge (TDS = 300–450 mg/L).
- The distribution of salinity in the Quaternary aquifer does not appear to have changed greatly between the 1940s–60s drilling program and the 1993–94 sampling program. However, all salinities may have increased by ~200–400 mg/L.

4.4.7.8 Water Balance of the Uley East Lens

A simple water balance for the Uley East lens, based on the conceptual model described above and shown in Figures 4.14–4.15, was constructed and is presented in Appendix C. Since the chloride mass balance is considered to provide a good estimate of average annual rainfall recharge across the groundwater lenses, the estimate from this method of 50 mm/y was used in the water balance calculation (see Section 4.4.7.2). In using the rainfall recharge estimate from the chloride mass balance method in the water balance calculations, the entire rainfall catchment area (87.5×10^6 m^2) must be used to estimate the total recharge to the lens.

The discrepancy in the water balance of 3083 ML/y is much larger than for the other two lenses. If the discrepancy was to be attributed to downward leakage to the Tertiary Sand aquifer, when applied across the whole lens area, this results in a leakage rate of 74 mm/y. This outcome suggests that downward leakage along the Uley East lens may be a much more significant process than for the Uley Wanilla lens.

5. APPLICATION OF THE CONCEPTUAL MODEL TO DEVLOPING THE NUMERICAL MODEL AND ITS LIMITATIONS

5.1 SUMMARY

A summary of the information provided in Chapter 4 is shown on Figures 4.13–4.15. This information, along with the discussion in Chapter 4, will be used to guide the development of the three dimensional numerical model of the Uley Basin, 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 groundwater flow in the lenses and Tertiary Sand aquifer can be compared with model results to ensure that the final model best represents the real system.

5.2 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 the Uley Basin and their likely impacts on the outcomes of the numerical model are described in Table 5.1. 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 negligible effect on the final outcome.

Table 5.1. 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) Poor knowledge of the extent and properties of the Tertiary Sand aquifer in the north of the Uley Basin.	Tertiary Sand layer modelled as constant thickness or flat bottomed in this area, with thickness based on that in south of study area.	This may have little or large impact on modelled water fluxes, groundwater heads and responses to pumping or climate change scenarios in the Quaternary aquifer. To be further investigated through numerical modelling exercise. Tertiary Sand may be thin or discontinuous in the northern part of the study area.

Limitation	Approach for Addressing This in the Numerical Model	Likely Impact on Outcomes of Numerical Model
(2) Little information on the spatial distribution of Quaternary Aquifer properties, particularly in the northern lenses.	Layer properties assigned based on information available, local experience of DWLBC staff, and calibration of the model results to both observed hydraulic head data and quantitative and qualitative information on groundwater flow dynamics provided in Chapter 4.	Calibration to both hydraulic head data and information on groundwater flow dynamics (e.g. groundwater residence times, etc) should minimise the impact of this. However, additional uncertainties in the model, such as inter-aquifer leakage may lead to non-uniqueness[1] in the calibration process and large uncertainties in the outcomes of the model.
(3) Little information on the spatial distribution of Tertiary Clay properties across the region. One K_v value is available. There is no information on K_H, porosity or storage parameters.	Properties applied uniformly, with the exception of areas where qualitative information on inter-aquifer leakage is available. Here, Tertiary Clay properties can be varied accordingly to allow / prevent inter-aquifer leakage, although magnitudes of leakage are uncertain.	Impact should be minimised by the qualitative calibration approach suggested. However, non-uniqueness may also be a problem. Actual impact of varying this parameter can be assessed during the modelling exercise.
(4) Little information on the spatial distribution of Tertiary Sand properties across the region. Tertiary Sand properties are available for one point only.	Application of uniform properties for this layer across the model domain.	Influence of Tertiary Sand on groundwater flow in the Quaternary aquifer can be assessed during the numerical modelling process. This limitation may have an impact ranging from insignificant to large. In determination of this through model calibration, non-uniqueness is likely to be a problem.
(5) Lack of information on the inflows to the Tertiary Sand in the north of the Uley Basin.	The water balance for the Tertiary Sand is completely unknown and hence there is no way of indirectly determining this. It is currently considered that there is little inflow to the Tertiary Sand in this area. However, model calibration may provide some guidance for this.	As for (4).
(6) Limited direct or indirect observational data on the occurrence of inter-aquifer leakage.	Use of qualitative information on inter-aquifer leakage provided in Chapter 4 (in Water Sources and Water Outflows sections) to guide modelling of this process.	As for (4).

1. Non-uniqueness is a problem affecting numerical models where there is more than one parameter affecting a calibration result (e.g. both aquifer properties and recharge rates may influence calibration of hydraulic heads) and both parameters are poorly constrained. Any combination of scenarios, where the parameters are varied within reasonable limits, including use of incorrect values, may lead to acceptable calibration, but cause incorrect predictions of system response to other scenarios

6. DEVELOPMENT OF A SIMPLE WATER BALANCE MODEL FOR PREDICTING TEMPORAL WATER TABLE VARIATIONS IN THE ULEY SOUTH LENS

6.1 INTRODUCTION AND OBJECTIVES

The majority of rainfall recharge estimates described in Chapter 4 give an indication of *average annual* recharge rates across the Quaternary aquifer groundwater lenses. However, the large variability in annual rainfall in the Uley Basin area (between 351–955 mm/y) and dynamic nature of the Quaternary groundwater system (i.e. its rapid response to rainfall) indicate that average annual recharge rates cannot be used in water balance calculations to match hydrograph responses or predict future groundwater levels under various management and climatic scenarios. As described in Section 4.3.1, due to a generally good agreement with the methods of Evans (1997), it is considered that the limiting winter rainfall recharge estimation method of Barnett (1978) may be useful in providing temporally variable estimates of recharge rates.

A simple water balance modelling exercise was carried out to investigate whether the method of Barnett (1978) could be used in a water balance to adequately predict changes in water table elevation in response to rainfall for the Uley South lens.

6.2 METHODOLOGY

6.2.1 GENERAL

A generic Microsoft Excel spreadsheet model was developed, as shown in Appendix E, to calculate the annual water balance for a groundwater lens and, from this, estimate changes in hydraulic head at a certain point. The model incorporates the following processes:

- Rainfall recharge (R), estimated as the difference between winter (May-October) rainfall and a specified base winter rainfall.
- Groundwater inflow (GW_I) from up gradient of the groundwater lens (can be specified as a total volume or calculated from a variable hydraulic gradient and specified aquifer parameters).
- Leakage into the lens (L_I) (e.g. upward leakage from the Tertiary Sand aquifer) (can be specified as a total volume or calculated from a variable hydraulic head gradient and specified aquitard parameters).
- Groundwater outflow (GW_O) from the lens at the down gradient boundary (can be specified as a total volume or calculated from a variable hydraulic gradient and specified aquifer parameters).

- Vertical leakage out of the lens (L_O) (e.g. downward leakage to the Tertiary Sand aquifer).
- Groundwater extraction (E) (as a total volume).

The water balance is calculated as follows:

ΔS = Inflow – Outflow

= $R + GW_I + L_I - GW_O - L_O - E$

where ΔS is the change in storage of the aquifer. This change in storage is converted to a change in hydraulic head using an aquifer area and specific yield (Sy).

The model uses one point in the lens as a reference, selected by the user. This point is an observation well in a desired location, for which a groundwater hydrograph is available for comparison with modelled results. A hydraulic head value from this hydrograph is used as the initial head for the model, and new hydraulic heads are calculated at the end of each time period for this point. The calculated hydraulic head at the reference point can also be used to calculate the hydraulic gradient between the point and a fixed reference point at the down-gradient boundary (e.g. sea level for the Uley South lens) for groundwater outflow calculations in the next time period. This allows the down-gradient outflow to fluctuate with hydraulic heads in the lens and rainfall. Hence, the distance used to calculate the hydraulic gradient is the distance of the selected reference point to the lens boundary (e.g. the coast).

6.2.2 APPLICATION OF THE MODEL TO THE ULEY SOUTH LENS

Information from Section 4.4.5 was used to parameterize the spreadsheet water balance model for the Uley South lens. The processes considered were:

- Rainfall recharge, with a base winter rainfall of 250 mm/y and annual winter (May – October) rainfall obtained from the Bureau of Meterorology's SILO website (Bureau of Meteorology, 1997–2006) and an area of application of 6.8 x 10^6 m^2, which is the area between the two groundwater flow divides shown on Map 1.
- Upward leakage from the Tertiary Sand, assuming a constant hydraulic head difference of 0.2 m, an aquitard thickness of 10 m, a Kv of 6.8 x 10-4 m/d, an aquitard porosity of 0.35 and a leakage area of 25 x 10^6 m^2 (approximately one third of the total modelled area).
- Down-gradient outflow to the Southern Ocean, which was allowed to fluctuate as the hydraulic head at the reference point, and hence the hydraulic gradient, varied.
- Groundwater extraction from the Uley South bore field, which commenced in 1976. Groundwater extraction data beyond 1999 was not available at the time of writing this report and hence a constant value of 5000 ML/y was applied for the years between 2000–05.

A specific yield value of 0.15 was used in the calculations of hydraulic head, which is at the upper end of the range calculated by Evans (1997) using water table recovery curves (Section 4.4.5.5). The reference point chosen for hydraulic head calculations (and hydrograph comparison), and calculation of the groundwater flux to the ocean, was observation well ULE114, which is located approximately at the centre of the Uley South lens, 4 km from the coast.

6.2.3 RESULTS AND DISCUSSION

The modelled hydraulic heads are compared with the observed hydrograph for ULE114 in Figure 6.1, and the variations over time in the magnitudes of the different components of the water balance are shown along with the calculated SWL at ULE 114 in Figure 6.2. Considering the simplicity of the water balance model, the trends in the hydrograph are represented reasonably well (Fig. 6.1), with the difference between observed and modelled heads ranging between 0.02–1.76 m (average 0.64 m) and an average percent difference between observed and modelled hydraulic heads of 14%.

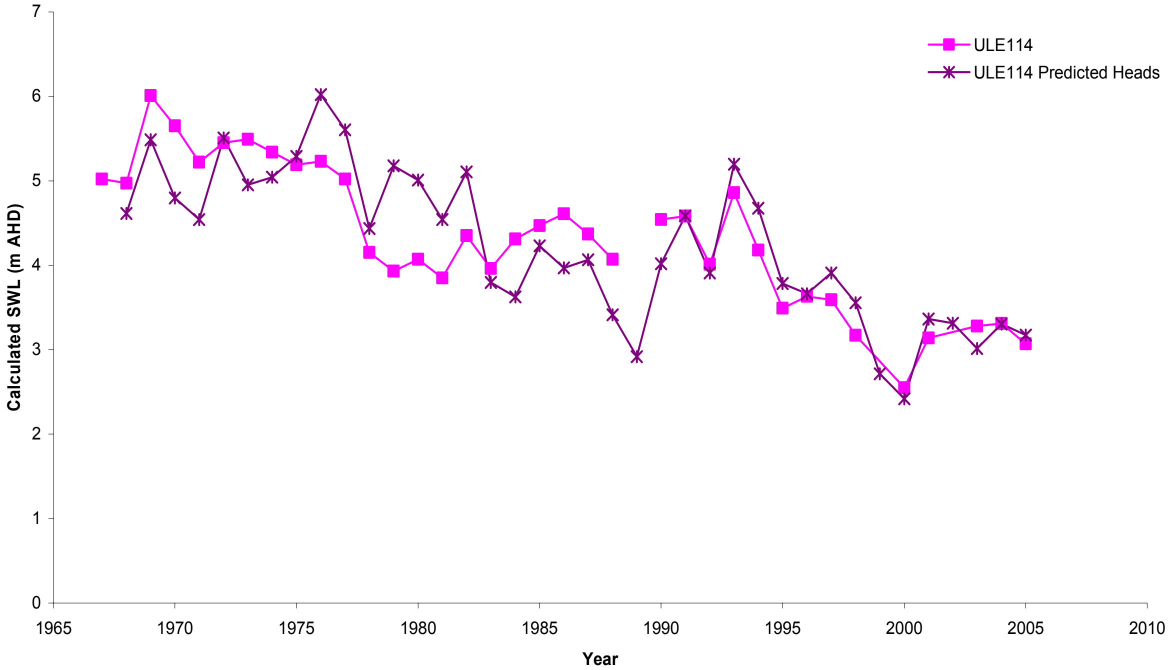


Figure 6.1. Modelled hydraulic heads at observation well ULE114, calculated using the simple water balance model for the Uley South lens and compared with the observed groundwater hydrograph for ULE114.

Figure 6.2 shows that rainfall recharge and down-gradient outflow are the largest components of the water balance for the Uley South lens. The modelled outflow to the Southern Ocean from the Uley South lens varies considerably, between 5.3 x 10^6 m^3/y and 1.3 x 10^7 m^3/y, as the hydraulic gradient changes in response to rainfall and groundwater extraction variations.

6.2.4 PREDICTIVE SCENARIOS: GROUNDWATER EXTRACTION = 10 000 ML/Y AND 20 000 ML/Y

To investigate the effects of increasing groundwater extraction, the water balance model was re-run using the same parameters, with the exception of groundwater extraction, which was set at 10 000 ML/y (Scenario 1) and 20 000 ML/y (Scenario 2) for the entire modelled time period. Figure 6.3 shows that, with groundwater extraction at 10 000 ML/y, predicted hydraulic heads at ULE114 drop to between ~0–2 m AHD, which is between 2–4 m above the aquifer bottom at that location. In response to these reduced hydraulic heads, the basin outflow to the Southern Ocean also drops to between 3.5 x 10^5 m^3/y and 5.7 x 10^6 m^3/y.

Figure 6.4 shows that, with groundwater extraction at 20 000 ML/y, predicted hydraulic heads at ULE114 drop to between ~-2 m AHD and –4.4 m AHD, which is below the aquifer bottom at that location. In this case, basin outflow to the Southern Ocean is calculated as a negative value due to the complete dewatering of the aquifer.

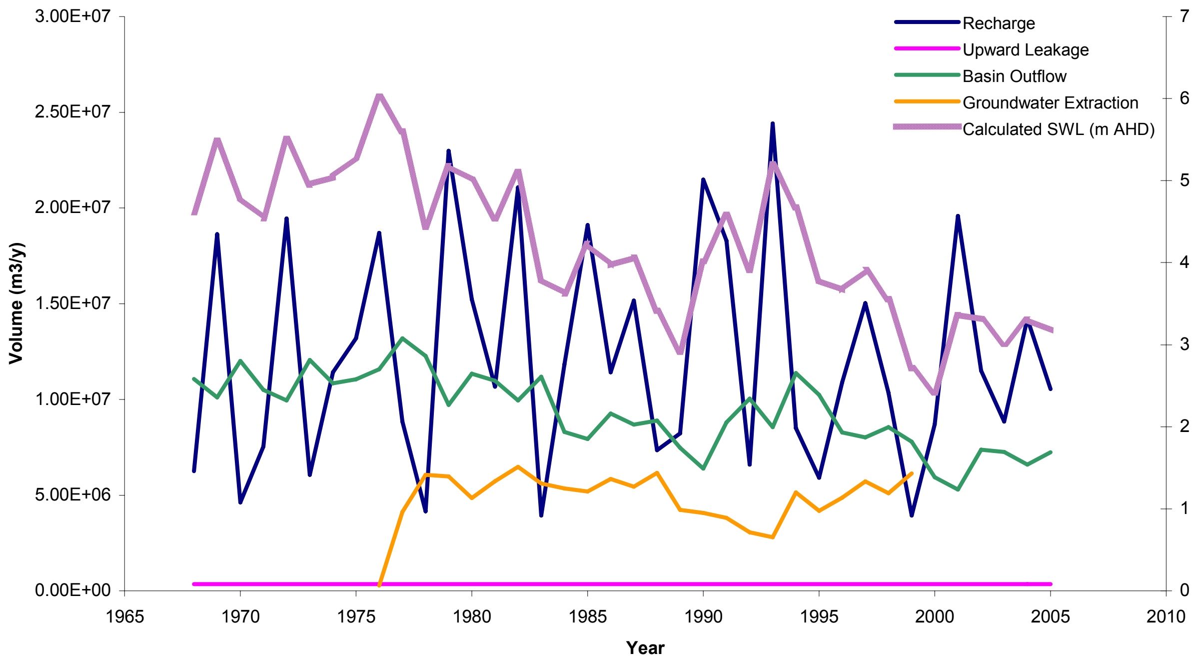


Figure 6.2. **Variations in the magnitudes of the various water balance components for the Uley South lens, as calculated using the simple water balance model.**

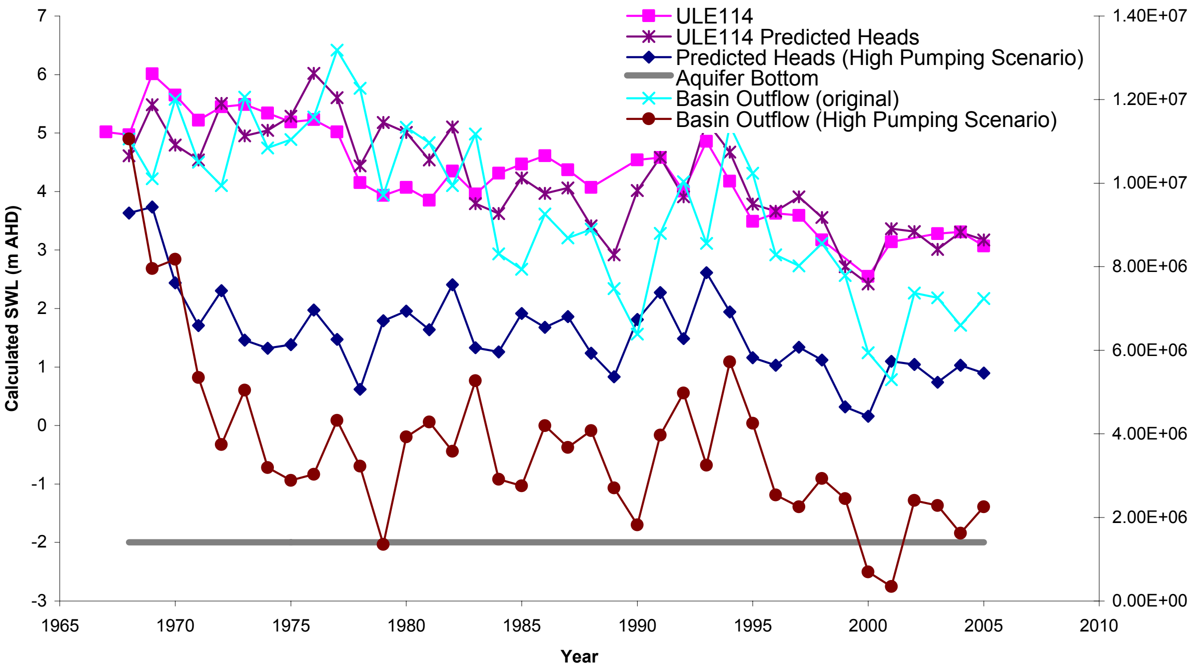


Figure 6.3. **Observed and calculated hydraulic heads for ULE114, with predicted hydraulic heads under a higher groundwater extraction scenario (10 000 ML/y). Calculated variations in the basin outflow to the Southern Ocean are also shown for the current and increased extraction scenario.**

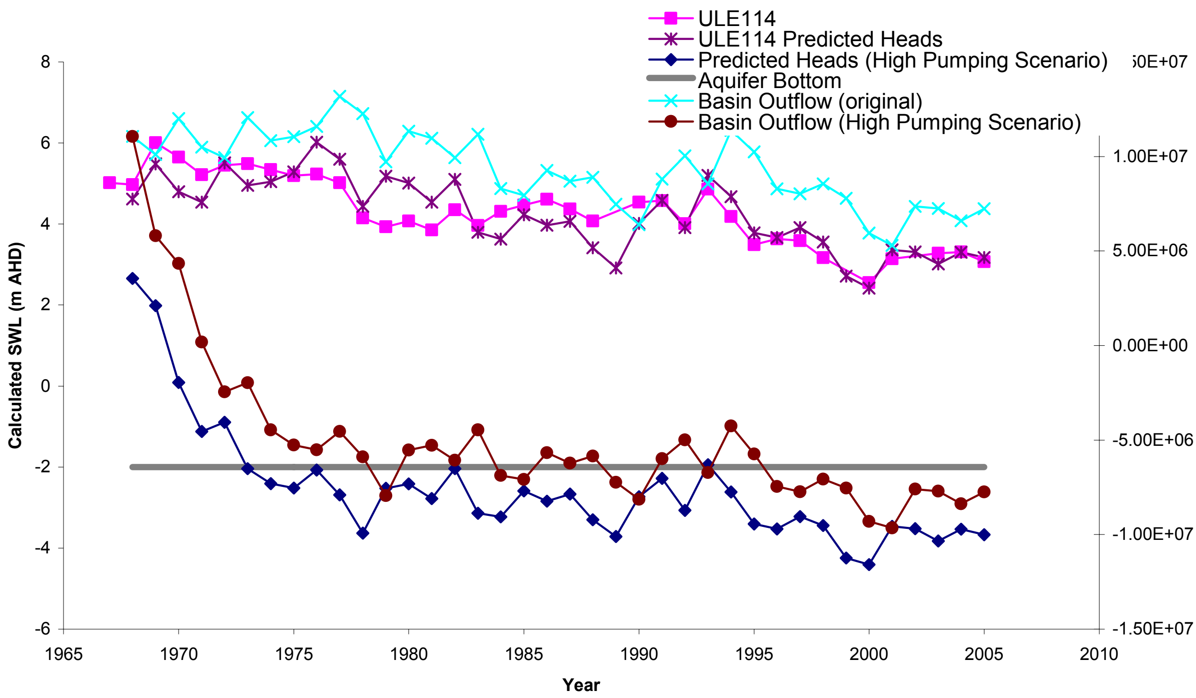


Figure 6.4. **Predicted hydraulic heads under an extreme groundwater extraction scenario (20 000 ML/y), showing that groundwater levels drop below the base of the aquifer in this case.**

7. SIMPLE PREDICTIONS FOR GROUNDWATER SALINITY UNDER A CLIMATE CHANGE SCENARIO BASED ON CHLORIDE MASS BALANCE CALCULATIONS

7.1 INTRODUCTION AND OBJECTIVE

As described in Section 4.2.1.3, a potential model for the observed increase in groundwater salinities in the Uley Basin above that of rainfall, in the absence of a concurrent increase in ^{2}H and ^{18}O enrichment of the water itself, is the complete evapotranspiration of summer rainfall and some transpiration of winter rainfall. The result is that any rainfall falling in summer is (almost) completely evaporated, with the dissolved salts left behind in the soil or on the ground surface to be remobilised by winter rainfall and recharged.

The objective of this chapter is to investigate the implications of this conceptual model for changes in groundwater salinities under a climate change scenario where there is a 10% shift in rainfall from winter to summer (i.e. winter rainfall decreases by 10% and summer rainfall increases by 10%).

7.2 METHODOLOGY

An extension of the chloride mass balance approach used by Evans (1997) to estimate average annual recharge rates for the groundwater lenses is used here, with the calculations shown in Appendix F. The assumption made is that all rainfall falling during summer, no matter how much, is evaporated, whilst there is a winter evapotranspiration amount that remains constant for each lens. Calculations are based on annual averages and do not reflect temporal variability in rainfall, recharge or recharge salinity.

7.3 RESULTS

The results of the chloride mass balance calculations shown in Appendix F are summarised in Table 7.1. Table 7.1 shows that, under the scenario of 10% increase in summer rainfall and 10% decrease in winter rainfall, resulting in an overall decrease in average annual rainfall from 570–541 mm/y, average groundwater salinities:

- In the Uley South lens would increase from 570–920 mg/L.
- In the Uley East lens would increase from 530–1785 mg/L.

In the case of the Uley Wanilla lens, the resulting recharge rate to the lens would be zero.

Table 7.1. Results of simple predictions for groundwater salinity under a climate change scenario based on chloride mass balance calculations.

	Uley South	Uley Wanilla	Uley East
Current Conditions			
Winter recharge (mm/y)	69	33	49
Average GW [Cl-] (mg/L)	115	140	93
TDS estimated from [Cl-] (mg/L)*	570	620	530
Climate Change Scenario			
Winter recharge (mm/y)	26	0	6
Average GW [Cl-] (mg/L)	291	–	721
TDS estimated from [Cl-] (mg/L)*	920	–	1785

The calculations shown in Appendix F indicate the winter evapotranspiration component of the water balance to be 361 mm/y for the Uley South lens, 397 mm/y for the Uley Wanilla lens and 381 mm/y for the Uley East lens. These values correspond to the 'limiting winter rainfall' of Barnett (1978) but are considerably higher than the estimate from that study of 217 mm/y for the Uley South lens.

The limiting winter rainfall used by Barnett (1978) was derived from a graph of change in SWL vs winter rainfall, with data from 1962–78. The point at which the graph intercepted the x axis (change in SWL = 0) corresponded to a winter rainfall of 217 mm/y. Figure 7.1 shows a similar plot of data for the Uley South lens, for 1961–94. This data is quite scattered, but a line of best fit indicates a limiting winter rainfall of ~315 mm/y. This result may indicate that a higher limiting rainfall value should be used in the simple water balance modelling described in Chapter 6 (250 mm was used).

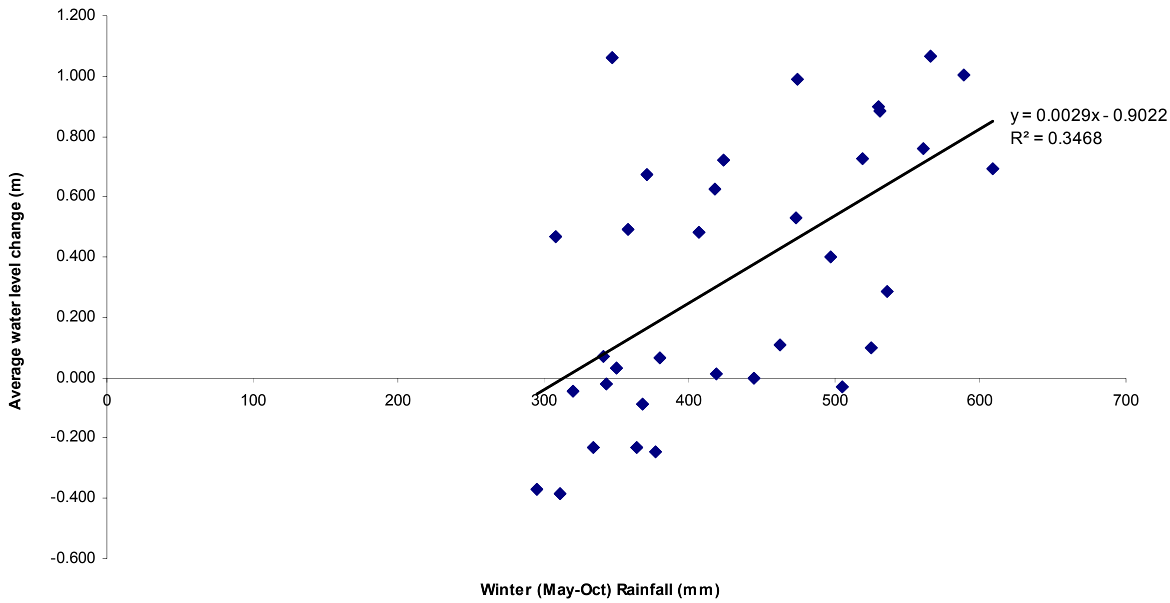


Figure 7.1. Plot of Change in SWL against winter rainfall for the Uley South lens (1961–94).

8. CONCLUSIONS AND RECOMMENDATIONS

A great deal of information already exists from previous studies on the hydrogeology of the Uley Basin and has been used in this report in the development of a conceptual model for groundwater flow and solute transport within the two main aquifer systems in the basin, the Quaternary aquifer groundwater lenses and the Tertiary Sand aquifer. Conclusions from the conceptual modelling exercise on the individual Quaternary groundwater lenses and the Tertiary Sand aquifer are summarised at the end of Sections 4.4.2, 4.4.5, 4.4.6 and 4.4.7 and on Figures 4.13–4.15. Some of the major conclusions from the conceptual modelling exercise are:

- All Quaternary aquifer groundwaters have residence times less than 30 yrs.
- Tertiary aquifer groundwaters generally have residence times greater than 35 yrs. One estimate of groundwater residence time in the Tertiary Sand below Big Swamp is 3000–6500 yrs.
- Similar chemical histories suggest that groundwater in the Tertiary Sand aquifer has been recharged through the Quaternary aquifer.
- The Quaternary aquifer is dynamic, responding rapidly to seasonal and longer term changes in rainfall.
- The major control on groundwater salinity in the Uley Basin is likely to be evapotranspiration of rainfall recharge, with (almost) all incident rainfall being evapotranspired in summer, leaving dissolved salts behind at the ground surface or in the thin soils of the basin to be dissolved and carried into the Quaternary aquifer by subsequent winter recharge.
- If this model of groundwater salinisation is accurate, a climate shift from winter dominated rainfall towards more summer rainfall with less falling in winter, under the same evapotranspiration conditions, is likely to have the greatest impact on Quaternary aquifer groundwater salinities.
- The chloride mass balance and water balance methods of Evans (1997) provide good spatially averaged estimates of average annual rainfall recharge to the groundwater lenses, whilst CFC data provides good point estimates of average annual recharge.
- The limiting winter rainfall method of Barnett (1978) may be the most useful in estimating temporal distributions of rainfall recharge across the three groundwater lenses, for use in the numerical modelling exercise. This should be guided by the average annual recharge estimates derived by Evans (1997).
- Leakage from Big Swamp controls groundwater salinity along the eastern portion of the Uley East lens and also influences groundwater salinities in the Tertiary Sand aquifer below this lens.
- Direct recharge to the Tertiary Sand aquifer occurs through the unsaturated Quaternary limestone aquifer in the central portion of the study area (between the Quaternary lenses).
- Groundwater residence times are greater in the Uley Wanilla lens (11–30 yrs) than in the other two Quaternary aquifer lenses (8–16 yrs). This is possibly an effect of high levels of groundwater extraction from this lens and the resulting disruption to the groundwater flow system, or preferential extraction of the shallowest, “youngest” groundwaters.

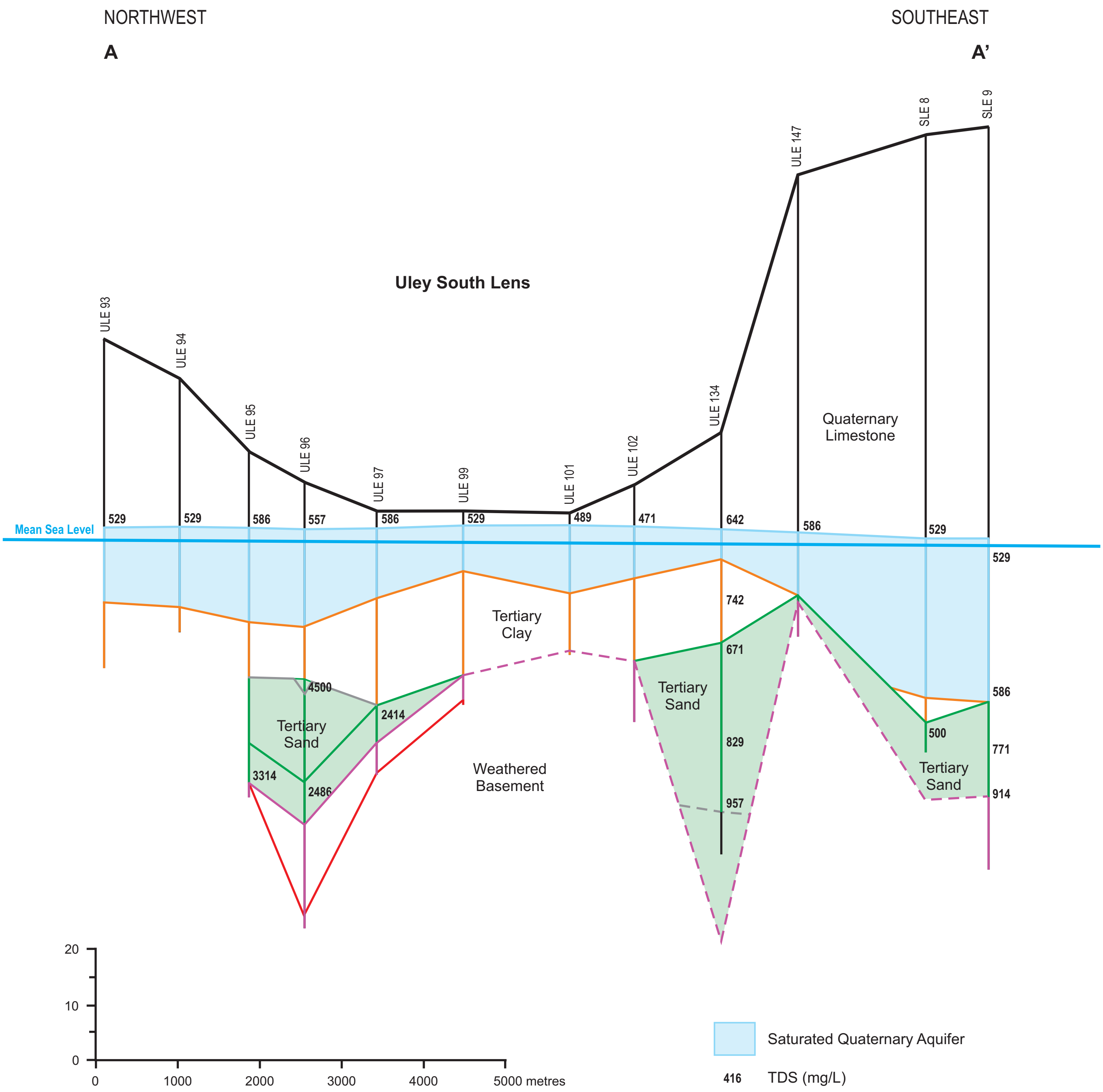
- Mass balance calculations suggest that downward leakage to the Tertiary Sand aquifer may be greater from the Uley East lens than from the other two lenses (App. C). Such leakage may occur anywhere along the Uley Wanilla and Uley East lenses as well as from their southern extremeties.
- Upward leakage from the Tertiary Sand to the Uley East lens, with a magnitude of the order of 14 mm/y, is possible in the zone to the south west of Cross Section BB', but is a relatively small component of the water budget for that lens.
- A simple mass balance model has been used to reasonably match trends in a groundwater hydrograph for the Uley South lens, providing overall confidence in the conceptual model of the lens and some quick and easy preliminary information on likely impacts on groundwater levels of different groundwater extraction scenarios. This methodology can probably also be applied to investigate various climate change scenarios.

Limitations of the conceptual model and their likely impacts on the outcomes of the numerical modelling exercise were summarised in Table 5.1. Due to the occasionally large gaps in quantitative data in some areas of the conceptual model and the problem that this implies for calibration of the numerical model, it is recommended that some of the semi-quantitative and qualitative information presented in this report be used in calibration and assessment of the final model along with the usual method of hydraulic head matching. Examples include qualitative information on groundwater flow and areas of inter-aquifer leakage, semi-quantitative information on likely ranges of groundwater residence times, flow rates and total fluxes.

It is also recommended that the numerical modelling process be used to determine which limitations provided in Table 5.1 are critical to the outcomes of the project, providing recommendations for a cost effective future field program in the Uley Basin.

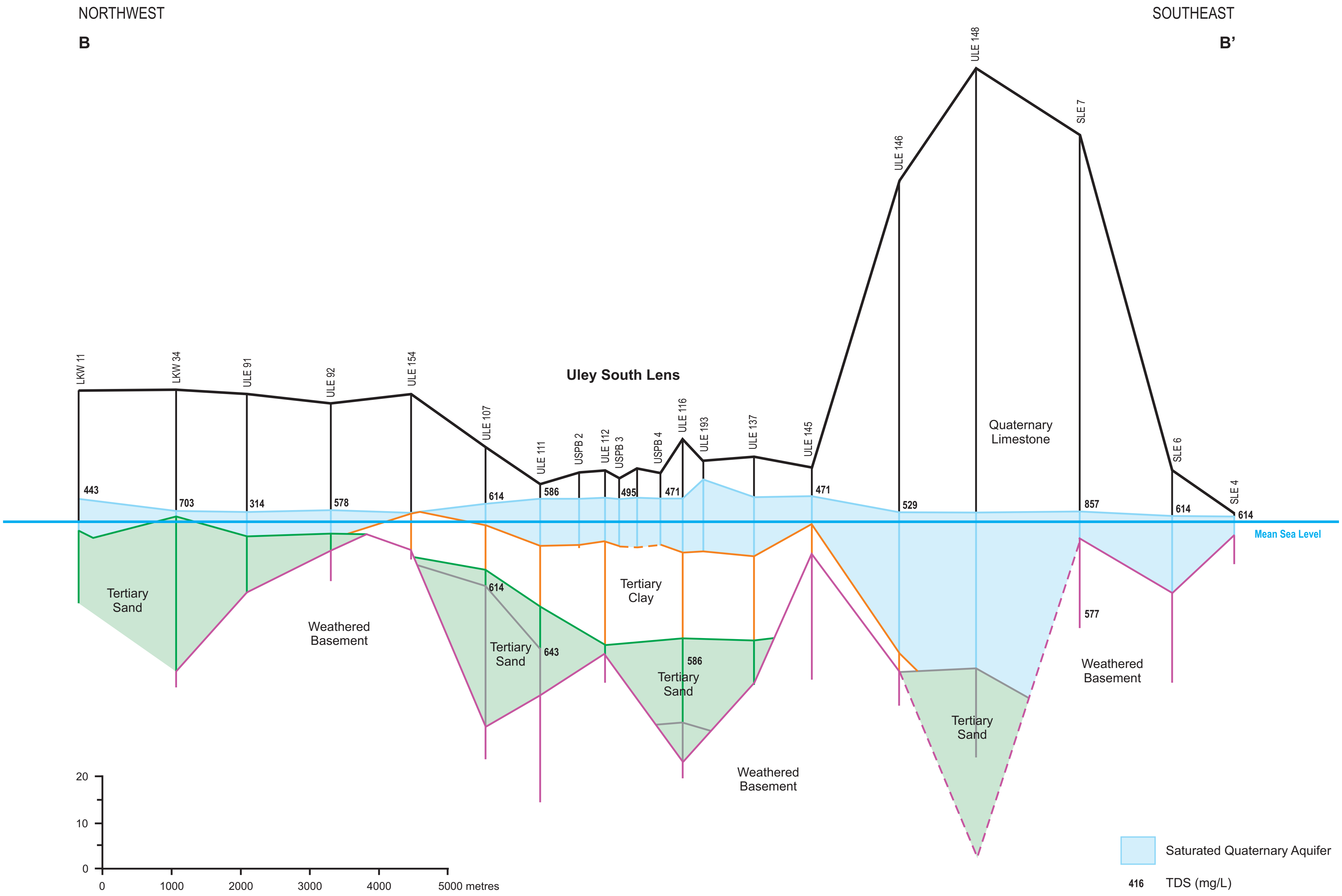
APPENDICES

A. HYDROGEOLOGICAL CROSS SECTIONS (FROM EVANS, 1997).



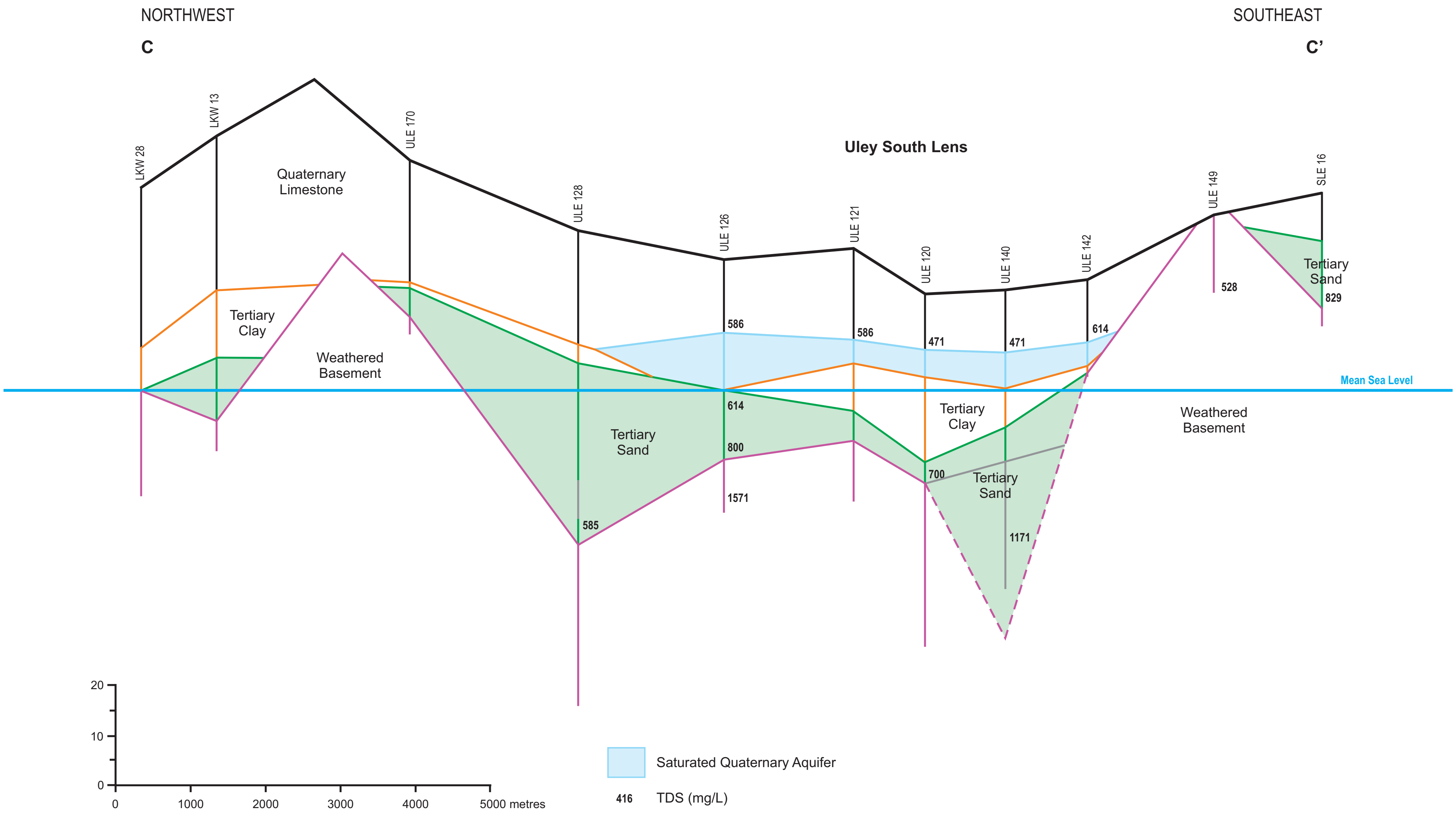
NORTHWEST
A
SOUTHEAST
A'
Uley South Lens
ULE 93
ULE 94
ULE 95
ULE 96
ULE 97
ULE 99
ULE 101
ULE 102
ULE 134
ULE 147
SLE 8
SLE 9
Mean Sea Level
529
529
586
557
586
529
489
471
642
586
529
529
742
671
829
957
586
500
771
914
4500
2414
3314
2486
Quaternary Limestone
Tertiary Clay
Tertiary Sand
Tertiary Sand
Tertiary Sand
Weathered Basement
20
10
0
0
1000
2000
3000
4000
5000 metres
Saturated Quaternary Aquifer
416
TDS (mg/L)

203301_009

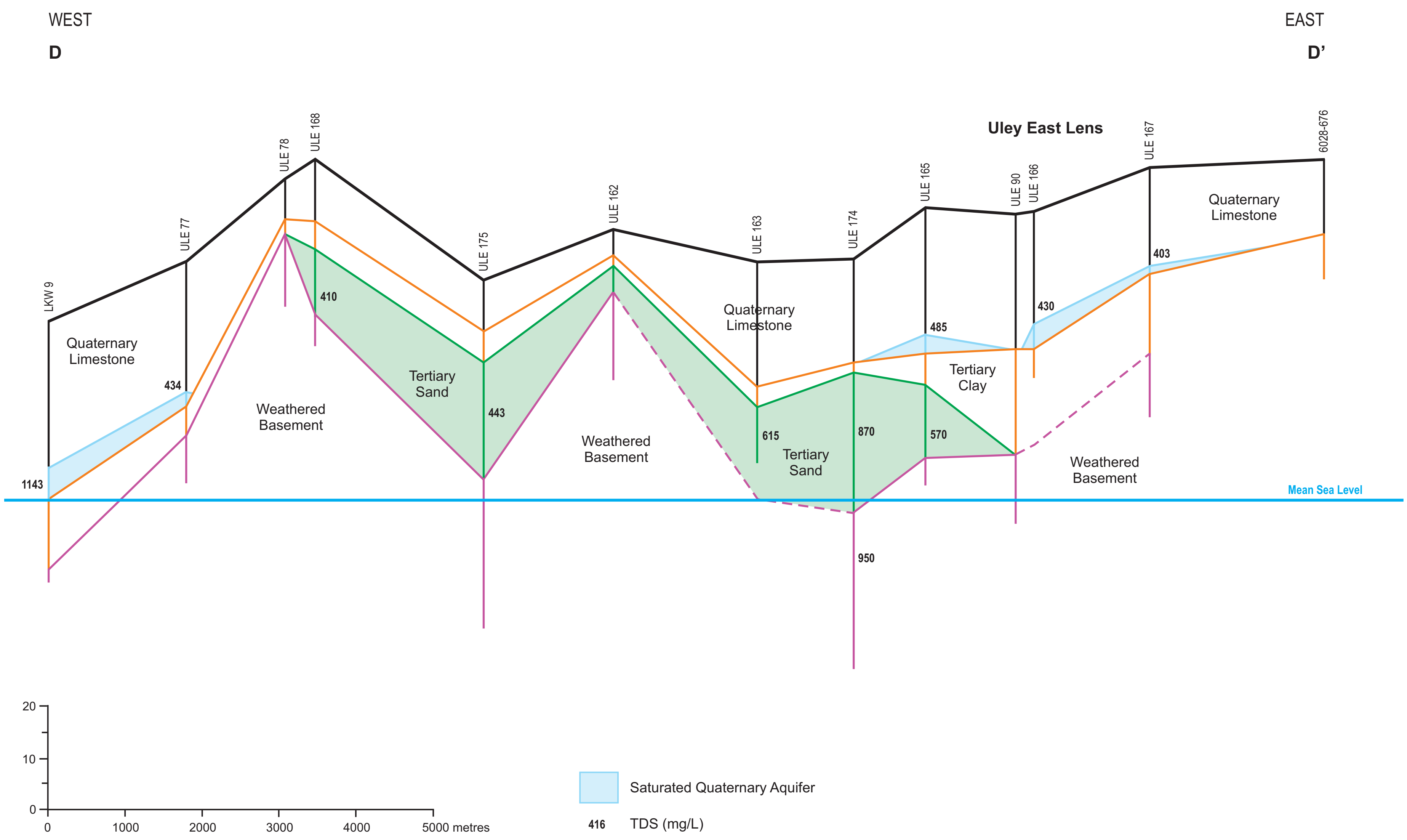


NORTHWEST
B
SOUTHEAST
B'
Uley South Lens
LKW 11
LKW 34
ULE 91
ULE 92
ULE 154
ULE 107
ULE 111
USPB 2
ULE 112
USPB 3
USPB 4
ULE 116
ULE 193
ULE 137
ULE 145
ULE 146
ULE 148
SLE 7
SLE 6
SLE 4
443
703
314
578
614
586
495
471
471
529
857
614
614
614
643
586
577
Quaternary Limestone
Tertiary Sand
Weathered Basement
Tertiary Sand
Tertiary Clay
Tertiary Sand
Weathered Basement
Tertiary Sand
Weathered Basement
Mean Sea Level
20
10
0
0
1000
2000
3000
4000
5000 metres
Saturated Quaternary Aquifer
416 TDS (mg/L)

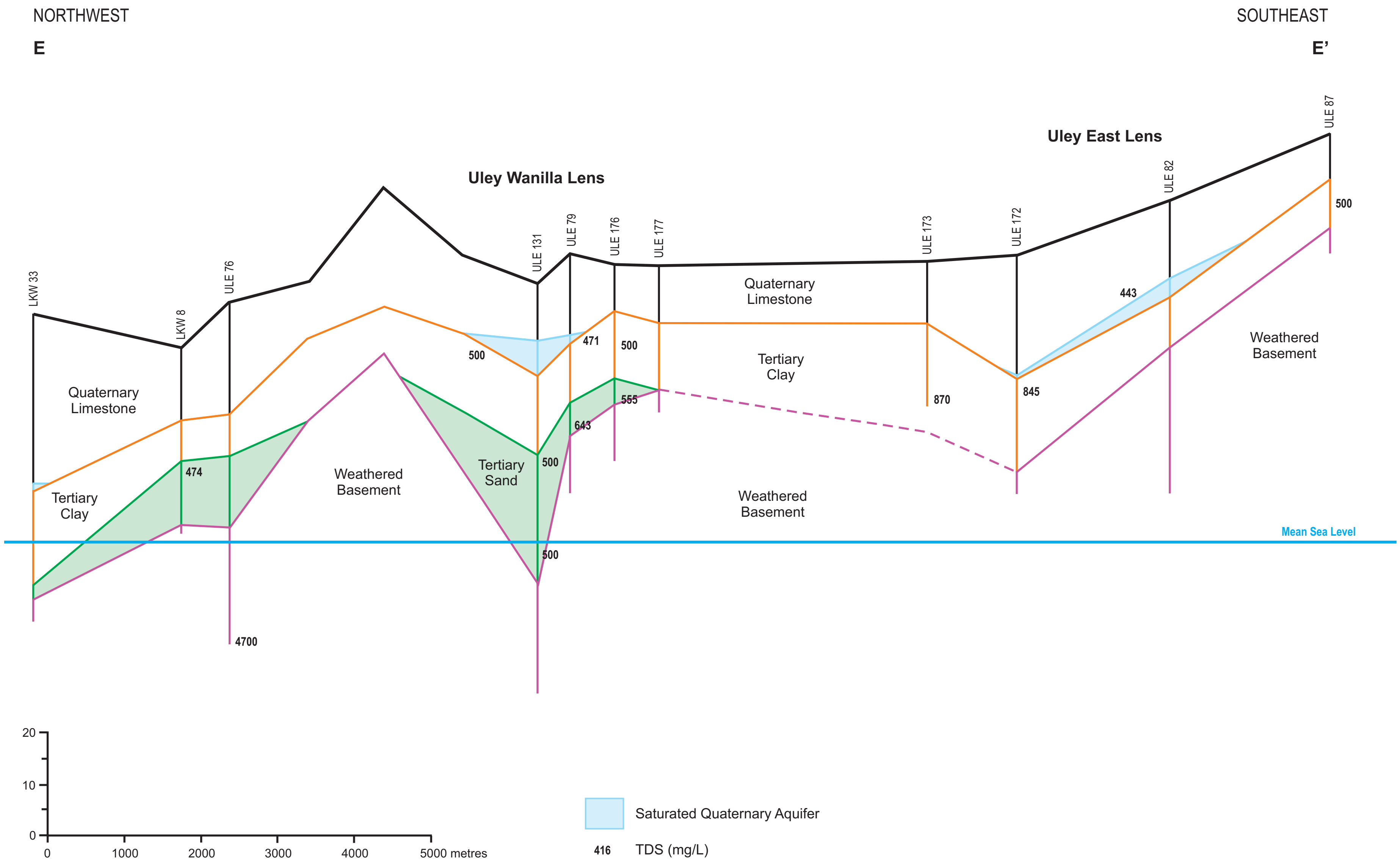
203301_010


NORTHWEST
C
SOUTHEAST
C'
Uley South Lens
LKW 28
LKW 13
ULE 170
ULE 128
ULE 126
ULE 121
ULE 120
ULE 140
ULE 142
ULE 149
SLE 16
Quaternary Limestone
Tertiary Clay
Weathered Basement
Tertiary Sand
Tertiary Clay
Tertiary Sand
Tertiary Sand
Weathered Basement
Mean Sea Level
586
586
471
471
614
528
829
614
800
700
585
1571
1171
20
10
0
0
1000
2000
3000
4000
5000 metres
Saturated Quaternary Aquifer
416 TDS (mg/L)

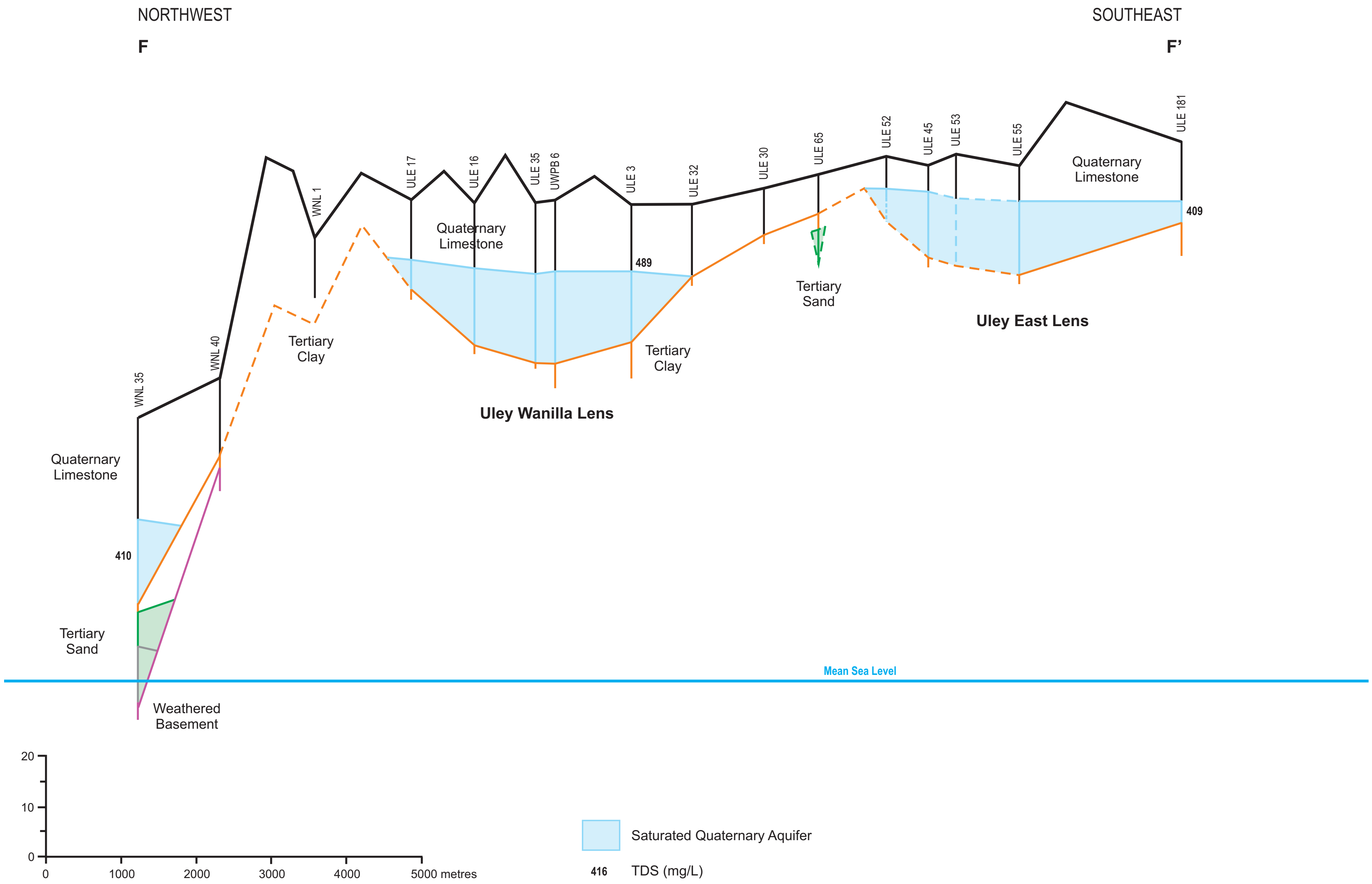
203301_011


WEST
D
EAST
D'
Uley East Lens
LKW 9
ULE 77
ULE 78
ULE 168
ULE 175
ULE 162
ULE 163
ULE 174
ULE 165
ULE 90
ULE 166
ULE 167
6028-676
Quaternary Limestone
Weathered Basement
Tertiary Sand
Tertiary Clay
Mean Sea Level
1143
434
410
443
615
870
950
485
570
430
403
20
10
0
0
1000
2000
3000
4000
5000 metres
Saturated Quaternary Aquifer
416 TDS (mg/L)

203301_012

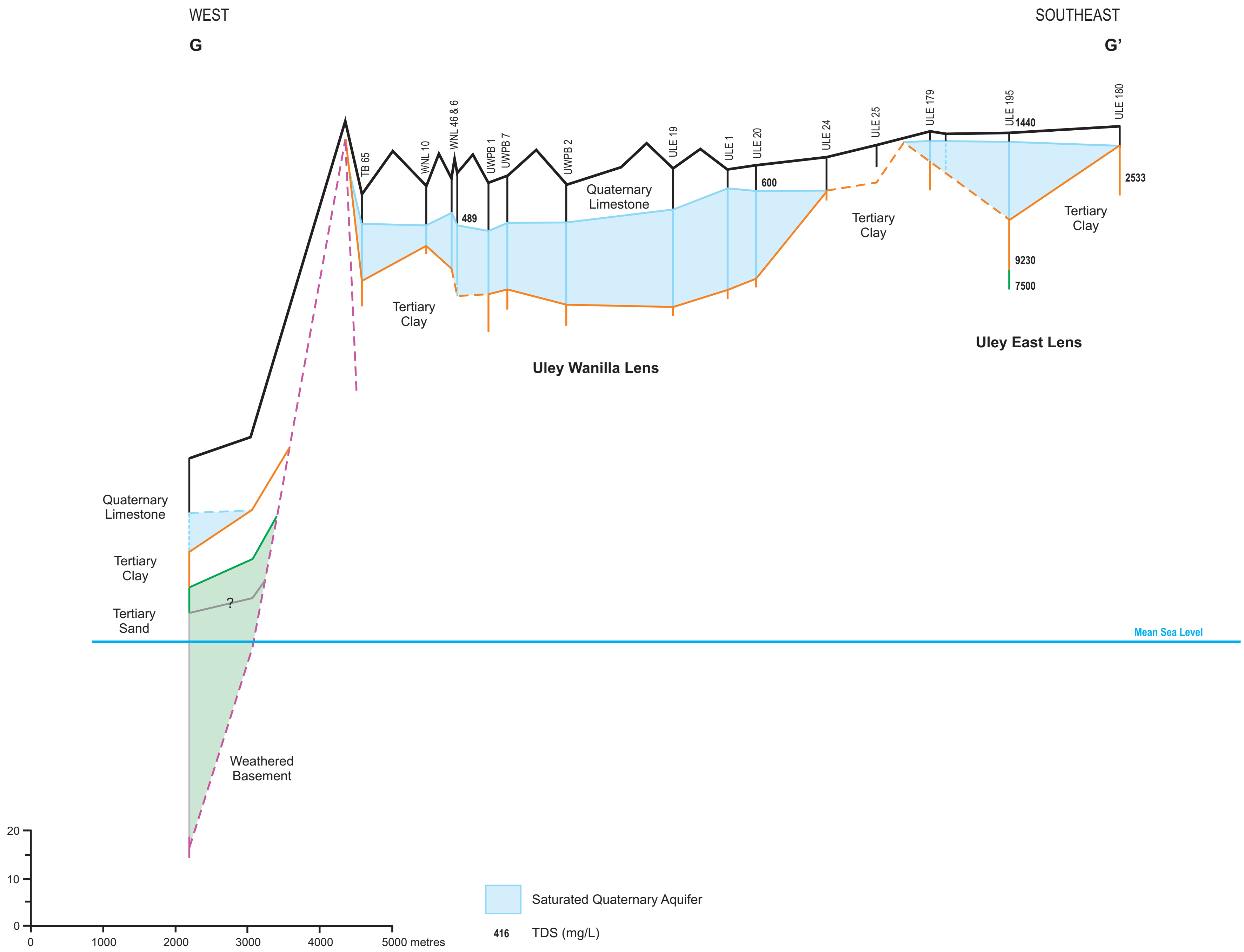

NORTHWEST
E
SOUTHEAST
E'
Uley Wanilla Lens
Uley East Lens
LKW 33
LKW 8
ULE 76
ULE 131
ULE 79
ULE 176
ULE 177
ULE 173
ULE 172
ULE 82
ULE 87
Quaternary Limestone
Tertiary Clay
Weathered Basement
Tertiary Sand
Quaternary Limestone
Tertiary Clay
Weathered Basement
Weathered Basement
474
4700
500
500
500
471
500
643
555
870
845
443
500
Mean Sea Level
20
10
0
0
1000
2000
3000
4000
5000 metres
Saturated Quaternary Aquifer
416
TDS (mg/L)

203301_013

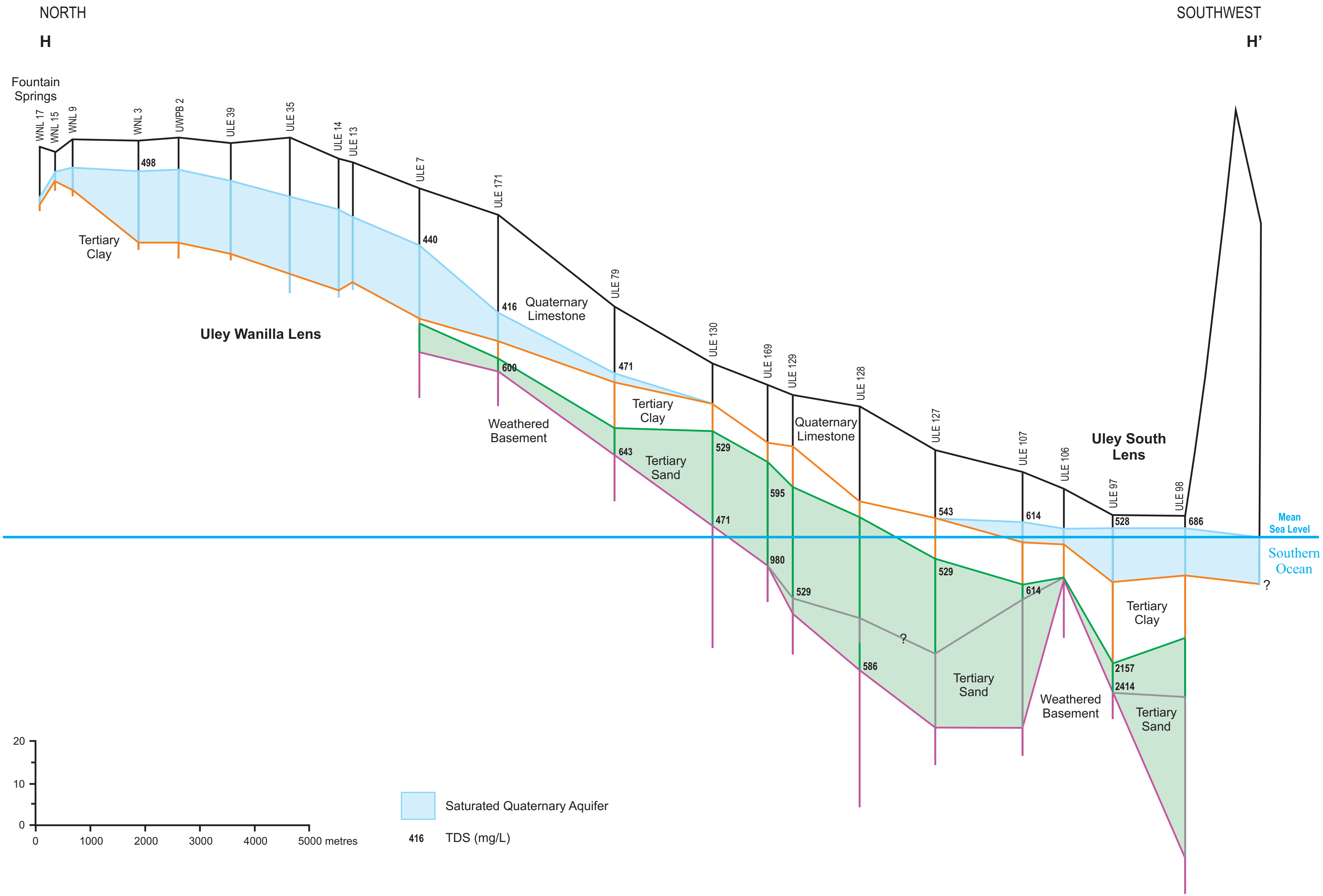


NORTHWEST
F
SOUTHEAST
F'
WNL 35
WNL 40
WNL 1
ULE 17
ULE 16
ULE 35
UWPB 6
ULE 3
ULE 32
ULE 30
ULE 65
ULE 52
ULE 45
ULE 53
ULE 55
ULE 181
Quaternary Limestone
Quaternary Limestone
Quaternary Limestone
Tertiary Clay
Tertiary Clay
Tertiary Sand
Tertiary Sand
Weathered Basement
410
489
409
Uley Wanilla Lens
Uley East Lens
Mean Sea Level
20
10
0
0
1000
2000
3000
4000
5000 metres
Saturated Quaternary Aquifer
416
TDS (mg/L)

203301_014

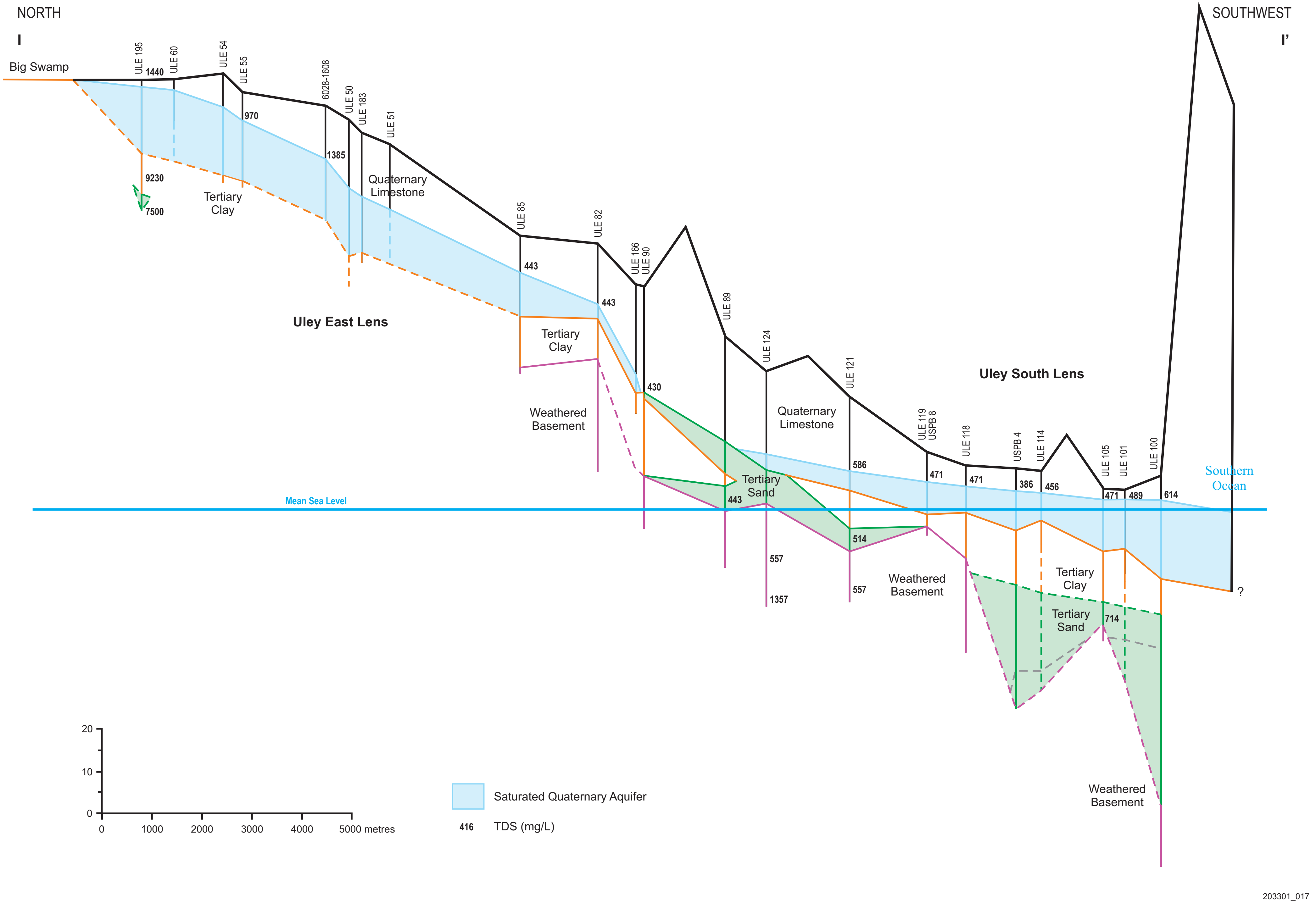

WEST
G
SOUTHEAST
G'
TB 65
WNL 10
WNL 46 & 6
UWPB 1
UWPB 7
UWPB 2
ULE 19
ULE 1
ULE 20
ULE 24
ULE 25
ULE 179
ULE 195
ULE 180
1440
2533
600
489
9230
7500
Quaternary Limestone
Tertiary Clay
Tertiary Clay
Tertiary Clay
Uley Wanilla Lens
Uley East Lens
Quaternary Limestone
Tertiary Clay
Tertiary Sand
?
Weathered Basement
Mean Sea Level
20
10
0
0
1000
2000
3000
4000
5000 metres
Saturated Quaternary Aquifer
416
TDS (mg/L)

203301_015



NORTH
H
SOUTHWEST
H'
Fountain Springs
WNL 17
WNL 15
WNL 9
WNL 3
UWPB 2
ULE 39
ULE 35
ULE 14
ULE 13
ULE 7
ULE 171
ULE 79
ULE 130
ULE 169
ULE 129
ULE 128
ULE 127
ULE 107
ULE 106
ULE 97
ULE 98
498
440
416
471
600
643
529
471
595
980
529
586
543
529
614
614
528
686
2157
2414
Tertiary Clay
Uley Wanilla Lens
Quaternary Limestone
Weathered Basement
Tertiary Clay
Tertiary Sand
Quaternary Limestone
Uley South Lens
Tertiary Sand
Weathered Basement
Tertiary Clay
Tertiary Sand
Mean Sea Level
Southern Ocean
20
10
0
0
1000
2000
3000
4000
5000 metres
Saturated Quaternary Aquifer
416 TDS (mg/L)

203301_016


NORTH
I
SOUTHWEST
I'
Big Swamp
ULE 195
1440
ULE 60
ULE 54
ULE 55
970
6028-1608
1385
ULE 50
ULE 183
ULE 51
9230
7500
Tertiary Clay
Quaternary Limestone
ULE 85
443
ULE 82
443
ULE 166
ULE 90
Uley East Lens
Tertiary Clay
Weathered Basement
430
ULE 89
ULE 124
ULE 121
Quaternary Limestone
Uley South Lens
Tertiary Sand
443
586
ULE 119
USPB 8
471
ULE 118
471
USPB 4
386
ULE 114
456
ULE 105
471
ULE 101
489
ULE 100
614
Southern Ocean
Mean Sea Level
514
557
1357
557
Weathered Basement
Tertiary Clay
Tertiary Sand
714
?
Weathered Basement
20
10
0
0
1000
2000
3000
4000
5000 metres
Saturated Quaternary Aquifer
416
TDS (mg/L)
203301_017

B. ANNUAL GROUNDWATER EXTRACTION FROM THE ULEY WANILLA AND ULEY SOUTH BOREFIELDS

Year	Uley Wanilla	Uley South
1949	1671	
1950	584	
1951	841	
1952	1015	
1953	1287	
1954	1671	
1955	1662	
1956	1774	
1957	2190	
1958	2472	
1959	2443	
1960	2733	
1961	2826	
1962	2667	
1963	795	
1964	13	
1965	392	
1966	817	
1967	1284	
1968	896	
1969	548	
1970	1443	
1971	1278	
1972	1176	
1973	1442	

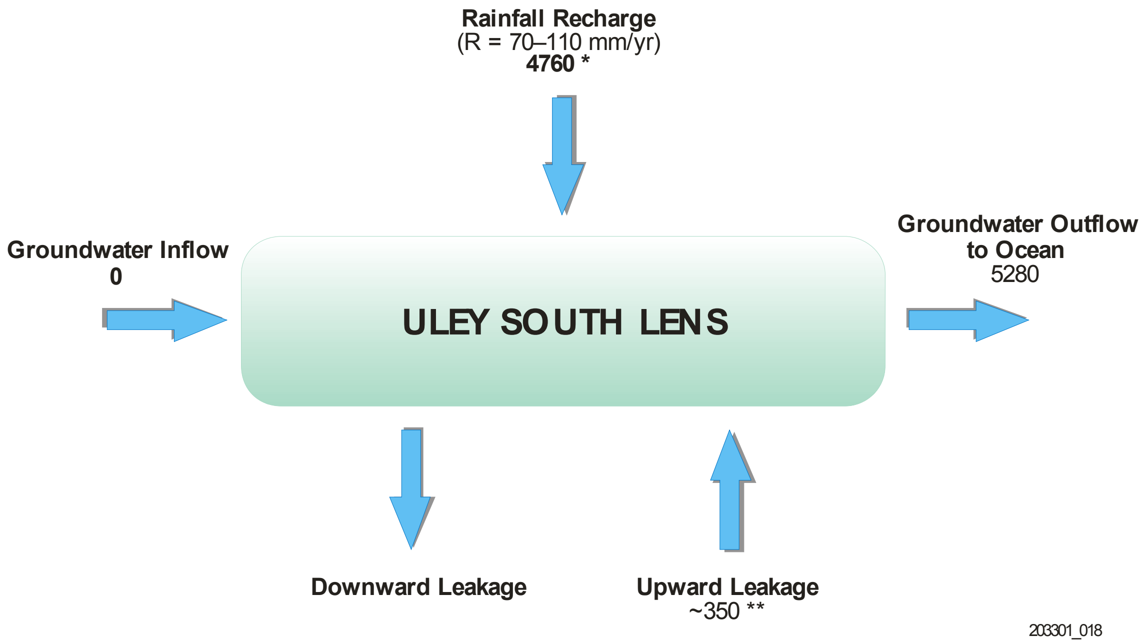
Year	Uley Wanilla	Uley South
1976	2656	278.0
1977	2584	4132.2
1978	323	6056.9
1979	399	5978.0
1980	461	4844.0
1981	922	5729.0
1982	723	6482.0
1983	535	5607.0
1984	646	5354.0
1985	662	5189.0
1986	681	5853.0
1987	1470	5434.0
1988	1293	6162.6
1989	1280	4232.7
1990	1394	4068.3
1991	1618	3807.1
1992	1929	3064.3
1993	1343	2794.0
1994	466	5132.0
1995		4173
1996		4856
1997		5714
1998		5105
1999		6133
2000		

2826

13

C. WATER BALANCES FOR THE QUATERNARY AQUIFER LENSES

Uley South Lens (area between groundwater divides shown on Map 1)



* Rainfall recharge estimated assuming the lower recharge rate of 70 mm/y, which was estimated by Evans (1997) using the chloride mass balance method, applied over the area between groundwater divides shown on Map 1 (68 x 106 m^2).

** Upward leakage estimated based on a leakage rate of 14 mm/y (Section 4.4.5.2) and an arbitrary area over which this leakage may occur of 25 x 106 m^2 (approximately one third of the total area).

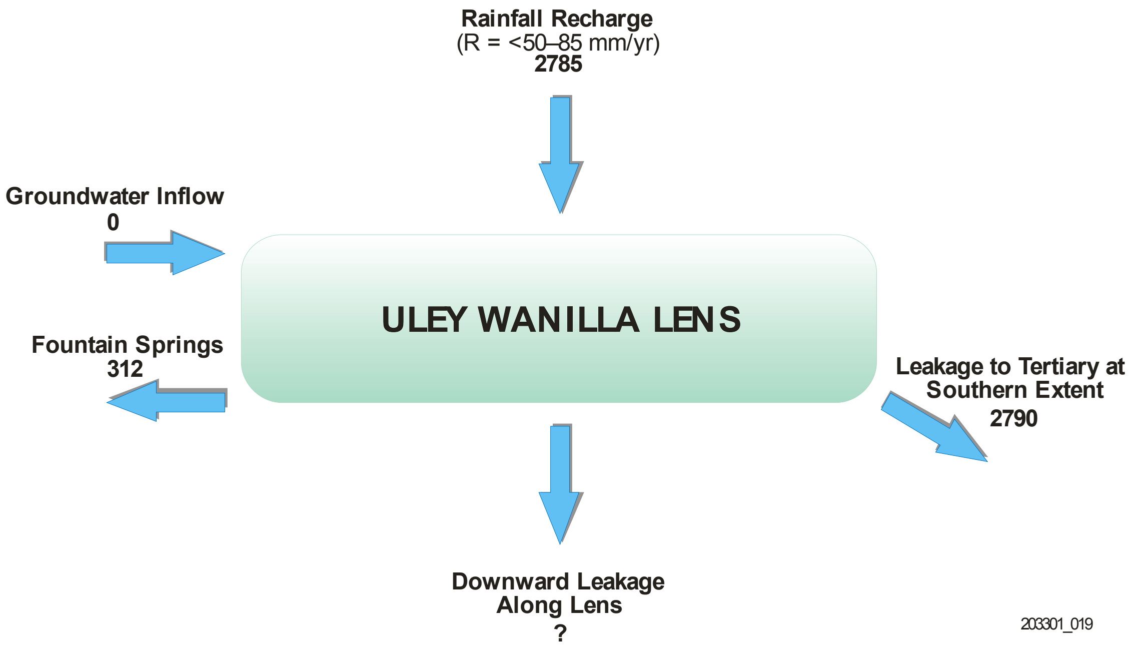
Water Balance (ML/y)

Inflow	Outflow
4760	5280
350	
5110	

Difference (Inflow – Outflow) = -170 ML/y

This difference in the mass balance is small compared with the magnitudes of the inflow and outflow components, suggesting that the water balance represents the system relatively well and there is no downward leakage from the lens to the Tertiary Sand aquifer. Due to the broad scale approach to estimating each of the components of the water balance, a discrepancy of this magnitude is not unexpected.

Uley Wanilla Lens



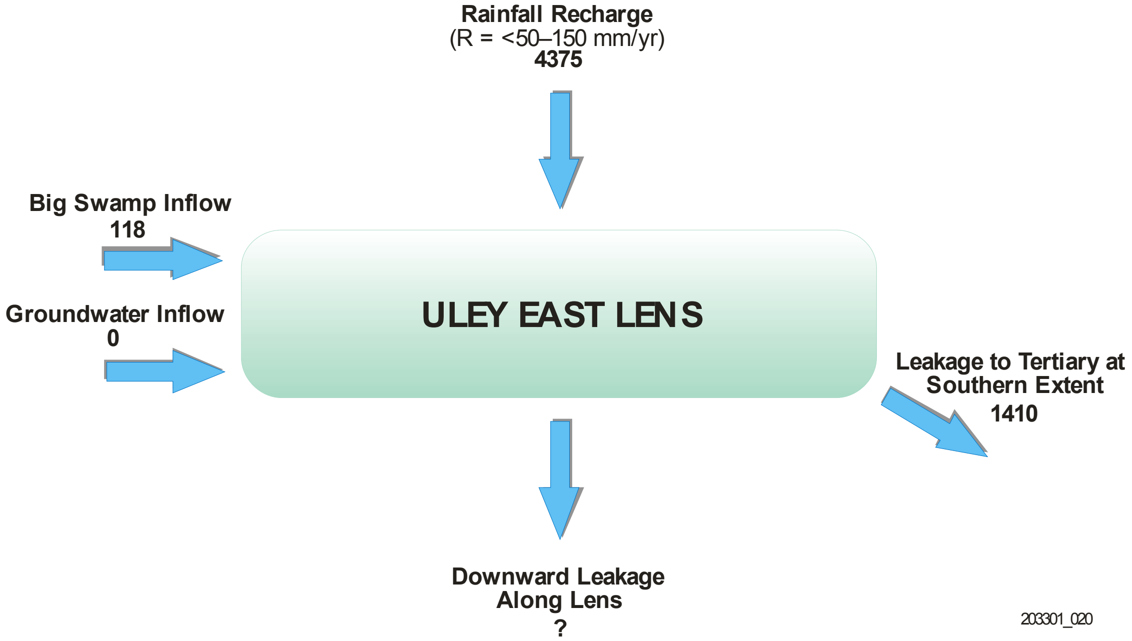
<u>Water Balance (ML/y)</u>

Inflow	**Outflow**
2785	2790
	<u>312</u>
	3102

Difference (Inflow – Outflow) = -317 ML/y

As described above for the Uley South lens, this difference is relatively small compared with the magnitudes of the components of the water balance and may simply be due to inaccuracies in estimates of the individual water balance components. However, if this difference can be attributed to downward leakage, the leakage rate, across the whole area of the lens would be ~8 mm/y.

Uley East Lens



Water Balance (ML/y)

Inflow	Outflow
4375	1410
118	
4493	

Difference (Inflow – Outflow) = 3083 ML/y

If this difference can be attributed to downward leakage from the Quaternary aquifer to the Tertiary Sand along the length of the Uley East lens, this implies a leakage across the entire lens (A = 41.6 x 10^6 m^2) of 74 mm/y.

D. CHLORIDE MASS BALANCE CALCULATIONS TO ESTIMATE RAINFALL RECHARGE ALONG THE EASTERN BOUNDARY OF ULEY EAST LENS

Average annual rainfall (P) = 570 mm/y

Average [Cl] rain (C_P) = 8 mg/L

Average [Cl] GW (C_R) = 93 mg/L

$$\text{Recharge} = \frac{PC_P}{C_R}$$

$$= \frac{570x8}{93}$$

= 49 mm/y

E. EXAMPLE OF WATER BALANCE SPREADSHEET CALCULATIONS FOR THE ULEY SOUTH LENS

General		***Up Gradient Inflow Parameters***		***Upward Leakage Parameters***		***Down Gradient Outflow Parameters***	
Study Basin:	Uley South	Aquifer thickness (m)		**Leakage Area (m2)**	2.50E+07	**Distance (point to ocean) (m)**	
Study Area Description:	Central Zone (production zone)	Hydraulic conductivity (m/d)		**Aquitard Thickness (m)**	10	**Aquifer Thickness (m)**	
Area of Study Area (m2):	6.80E+07	Cross section length (m)		**Kv (m/d)**	6.80E-04	**Hydraulic conductivity (m/d)**	
Aquifer Sy	0.15			**porosity**	0.35	**Cross section length (m)**	
Base rainfall (mm)	250						
(winter rainfall at which no rech occurs)							

Study Time Period:	Jan1967-Jan1968	Jan1968-Jan1969	Jan1969-Jan1970	Jan1970-Jan1971	Jan1971-Jan1972	Jan1972-Jan1973	Jan1973-Jan1974	Jan1974-Jan1975	Jan1975-Jan1976	Jan1976-Jan1977	Jan1977-Jan1978	Jan1978-Jan1979
Observed Change in SWL (m):	-0.05	1.04	-0.36	-0.43	0.237	0.037	-0.15	-0.15	0.04	-0.21	-0.87	-0.22
(+ve=rise; -ve=drop)												
Starting Head (m)	5.05	4.61	5.48	4.80	4.54	5.51	4.95	5.04	5.29	6.02	5.60	4.44
Final head	5.00	6.04	5.68	5.25	5.49	5.52	5.37	5.22	5.26	5.05	4.15	3.93
Average winter rainfall (mm/y):	342	524	318	361	536	339	418	444	525	380	311	588
Inflows												
Up-gradient Inflow												
Up-gradient Inflow (m3/y):	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
or												
Hydraulic gradient (m/m)												
Up-gradient Inflow (m3/y)	0	0	0	0	0	0	0	0	0	0	0	0
Upward Leakage												
Leakage (mm/y)	0	0	0	0	0	0	0	0	0	0	0	0
Total Leakage (m3/y)	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
or												
Head Quaternary (m) ULE196	0	0	0	0	0	0	0	0	0	0	0	0
Head Tertiary (m) ULE 135	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Hydraulic gradient (m/m)	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Leakage (mm/y)	1.42E+01	1.42E+01	1.42E+01	1.42E+01	1.42E+01	1.42E+01	1.42E+01	1.42E+01	1.42E+01	1.42E+01	1.42E+01	1.42E+01
Total Leakage (m3/y)	3.55E+05	3.55E+05	3.55E+05	3.55E+05	3.55E+05	3.55E+05	3.55E+05	3.55E+05	3.55E+05	3.55E+05	3.55E+05	3.55E+05
Inflow (m3/y)	3.55E+05	3.55E+05	3.55E+05	3.55E+05	3.55E+05	3.55E+05	3.55E+05	3.55E+05	3.55E+05	3.55E+05	3.55E+05	3.55E+05
Outflows												
Down Gradient Outflow												
Down-gradient outflow (m3):												
or												
Head difference (m) ULE114	5.05	4.61	5.48	4.80	4.54	5.51	4.95	5.04	5.29	6.02	5.60	4.44
Hydraulic gradient (m/m)	0.0012625	0.001153458	0.001371161	0.001198788	0.001135092	0.001376738	0.001238168	0.001261017	0.001322293	0.001505413	0.001400735	0.001109072
Down Gradient Outflow (m3/y)	11059500	10104288.87	12011367.18	10501384.56	9943404.096	12060225.32	10846352.57	11046505.44	11583284.32	13187413.61	12270438.67	9715467.174
Groundwater Extraction												
Groundwater extraction (ML/y)										278	4132	6057
Groundwater extraction (m3/y)	0	0	0	0	0	0	0	0	0	278000	4132000	6057000
Leakage												
Leakage (mm/y)	0	0	0	0	0	0	0	0	0	0	0	0
Leakage area (m2)												
Total Leakage (m3/y)	0	0	0	0	0	0	0	0	0	0	0	0
Outflow	1.11E+07	1.01E+07	1.20E+07	1.05E+07	9.94E+06	1.21E+07	1.08E+07	1.10E+07	1.16E+07	1.35E+07	1.64E+07	1.58E+07
Rainfall Recharge												
Recharge (mm/y)	92	274	68	111	286	89	168	194	275	130	61	338
Actual recharge (mm/y)	92	274	68	111	286	89	168	194	275	130	61	338
Recharge (m3/y)	6.26E+06	1.86E+07	4.62E+06	7.55E+06	1.94E+07	6.05E+06	1.14E+07	1.32E+07	1.87E+07	8.84E+06	4.15E+06	2.30E+07
or												
Set recharge (mm/y)												
Total Inflow (m3/y)	6.61E+06	1.90E+07	4.98E+06	7.90E+06	1.98E+07	6.41E+06	1.18E+07	1.35E+07	1.91E+07	9.19E+06	4.50E+06	2.33E+07
Total Outflow (m3/y)	1.11E+07	1.01E+07	1.20E+07	1.05E+07	9.94E+06	1.21E+07	1.08E+07	1.10E+07	1.16E+07	1.35E+07	1.64E+07	1.58E+07
Change in Storage (m3/y)	-4448928.571	8882282.563	-7032795.752	-2598813.135	9859167.333	-5653653.889	932218.8578	2500065.985	7471287.112	-4270842.18	-11899867.24	7566104.255
Calculated Change in SWL (m):	-4.36E-01	8.71E-01	-6.89E-01	-2.55E-01	9.67E-01	-5.54E-01	9.14E-02	2.45E-01	7.32E-01	-4.19E-01	-1.17E+00	7.42E-01
% Difference	772.3389356	-16.26807539	91.52493878	-40.74753455	307.8417859	-1598.053495	-160.9293371	-263.4030056	1731.197822	99.38572267	34.09812081	-437.1704213
New head (m)	4.613830532	5.484642548	4.795152769	4.540367167	5.5069522	4.952672407	5.044066412	5.289170921	6.021650049	5.602940032	4.436286381	5.178061308
%diff new head	7.723389356	9.194659798	15.57829633	13.51681586	0.36362675	10.34264289	6.139441526	1.247529111	14.39304805	10.86149647	6.898467005	31.75728518
Difference in new head (m)	0.39	0.56	0.88	0.71	0.02	0.57	0.33	0.07	0.76	0.55	0.29	1.25

Outward Leakage

4000	Leakage Area (m2)
10	
800	
3000	

Jan1979-Jan1980	Jan1980-Jan1981	Jan1981-Jan1982	Jan1982-Jan1983	Jan1983-Jan1984	Jan1984-Jan1985	Jan1985-Jan1986	Jan1986-Jan1987	Jan1987-Jan1988	Jan1988-Jan1989	Jan1989-Jan1990	Jan1990-Jan1991	Jan1991-Jan1992	Jan1992-Jan1993
0.14	0.12	0.16	-0.39	0.35	0.56	-0.26	-0.24	-0.3			-0.64	0.11	0.85
5.18	5.01	4.54	5.10	3.79	3.62	4.23	3.97	4.06	3.41	2.92	4.02	4.58	3.91
4.07	4.19	4.35	3.96	4.31	4.87	4.61	4.37	4.07		4.54	3.90	4.01	4.86
474	407	560	308	424	531	418	473	358	371	566	519	347	609
0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0
0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
0	0	0	0	0	0	0	0	0	0	0	0	0	0
0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
1.42E+01	1.42E+01	1.42E+01	1.42E+01	1.42E+01	1.42E+01	1.42E+01	1.42E+01	1.42E+01	1.42E+01	1.42E+01	1.42E+01	1.42E+01	1.42E+01
3.55E+05	3.55E+05	3.55E+05	3.55E+05	3.55E+05	3.55E+05	3.55E+05	3.55E+05	3.55E+05	3.55E+05	3.55E+05	3.55E+05	3.55E+05	3.55E+05
3.55E+05	3.55E+05	3.55E+05	3.55E+05	3.55E+05	3.55E+05	3.55E+05	3.55E+05	3.55E+05	3.55E+05	3.55E+05	3.55E+05	3.55E+05	3.55E+05
5.18	5.01	4.54	5.10	3.79	3.62	4.23	3.97	4.06	3.41	2.92	4.02	4.58	3.91
0.001294515	0.001252079	0.001134882	0.001276157	0.000948643	0.000906228	0.001057454	0.000991921	0.001015851	0.000853246	0.000729352	0.001004363	0.001146039	0.000977026
11339954.26	10968216.18	9941568.928	11179134.17	8310113.347	7938555.817	9263294.463	8689230.4	8898856.562	7474436.519	6389127.249	8798222.617	10039297.51	8558744.556
5978	4844	5729	6482	5607	5354	5189	5853	5434	6163	4233	4068	3807	3064
5978000	4844000	5729000	6482000	5607000	5354000	5189000	5853000	5434000	6163000	4233000	4068000	3807000	3064000
0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0
1.73E+07	1.58E+07	1.57E+07	1.77E+07	1.39E+07	1.33E+07	1.45E+07	1.45E+07	1.43E+07	1.36E+07	1.06E+07	1.29E+07	1.38E+07	1.16E+07
224	157	310	58	174	281	168	223	108	121	316	269	97	359
224	157	310	58	174	281	168	223	108	121	316	269	97	359
1.52E+07	1.07E+07	2.11E+07	3.94E+06	1.18E+07	1.91E+07	1.14E+07	1.52E+07	7.34E+06	8.23E+06	2.15E+07	1.83E+07	6.60E+06	2.44E+07
1.56E+07	1.10E+07	2.14E+07	4.30E+06	1.22E+07	1.95E+07	1.18E+07	1.55E+07	7.70E+06	8.58E+06	2.18E+07	1.86E+07	6.95E+06	2.48E+07
1.73E+07	1.58E+07	1.57E+07	1.77E+07	1.39E+07	1.33E+07	1.45E+07	1.45E+07	1.43E+07	1.36E+07	1.06E+07	1.29E+07	1.38E+07	1.16E+07
-1731382.835	-4781644.756	5764002.501	-13362562.74	-1730541.918	6170015.611	-2673723.035	976341.0287	-6634285.133	-5054865.09	11220444.18	5780348.811	-6895726.08	13143826.87
-1.70E-01	-4.69E-01	5.65E-01	-1.31E+00	-1.70E-01	6.05E-01	-2.62E-01	9.57E-02	-6.50E-01	-4.96E-01	1.10E+00	5.67E-01	-6.76E-01	1.29E+00
-221.2452966	-490.6572513	253.1864277	235.9115823	-148.4745635	8.01848059	0.819118953	-139.883212	116.8067037	#DIV/0!	#DIV/0!	-188.54701	-714.5923423	51.60123267
5.008317892	4.539529191	5.104627475	3.794572304	3.624911332	4.229814823	3.967685114	4.063404823	3.412984712	2.917409703	4.01745325	4.584154114	3.908102537	5.196713015
23.05449367	8.341985463	17.34775805	4.17746706	15.89532872	13.14548617	13.93307779	7.015907945	16.14288178		11.50984031	17.54241317	2.54108386	6.928251334
0.94	0.35	0.75	0.17	0.69	0.64	0.64	0.31	0.66		0.52	0.68	0.10	0.34

no extraction data

Jan1993-Jan1994	Jan1994-Jan1995	Jan1995-Jan1996	Jan1996-Jan1997	Jan1997-Jan1998	Jan1998-Jan1999	Jan1999-Jan2000	Jan2000-Jan2001	Jan2001-Jan2002	Jan2002-Jan2003	Jan2003-Jan2004	Jan2004-Jan2005
-0.68											
5.20	4.68	3.78	3.66	3.91	3.56	2.71	2.42	3.36	3.31	3.01	3.30
4.18		4.18	4.18	4.18	4.18	4.18	4.18	4.18	4.18	4.18	4.18
375	337	410	471	402	308	378	538	419	380	459	405
0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
0	0	0	0	0	0	0	0	0	0	0	0
0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
1.42E+01	1.42E+01	1.42E+01	1.42E+01	1.42E+01	1.42E+01	1.42E+01	1.42E+01	1.42E+01	1.42E+01	1.42E+01	1.42E+01
3.55E+05	3.55E+05	3.55E+05	3.55E+05	3.55E+05	3.55E+05	3.55E+05	3.55E+05	3.55E+05	3.55E+05	3.55E+05	3.55E+05
3.55E+05	3.55E+05	3.55E+05	3.55E+05	3.55E+05	3.55E+05	3.55E+05	3.55E+05	3.55E+05	3.55E+05	3.55E+05	3.55E+05
5.20	4.68	3.78	3.66	3.91	3.56	2.71	2.42	3.36	3.31	3.01	3.30
0.001299178	0.00116878	0.000945743	0.000915764	0.000977148	0.000889323	0.000678615	0.000604618	0.000840944	0.000828197	0.000753186	0.000825947
11380801.5	10238516.81	8284705.008	8022091.033	8559817.706	7790473.653	5944668.175	5296450.344	7366670.459	7255002.138	6597909.662	7235298.806
2794	5132	4173	4856	5714	5105	6133	5000	5000	5000	5000	5000
2794000	5132000	4173000	4856000	5714000	5105000	6133000	5000000	5000000	5000000	5000000	5000000
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
1.42E+07	1.54E+07	1.25E+07	1.29E+07	1.43E+07	1.29E+07	1.21E+07	1.03E+07	1.24E+07	1.23E+07	1.16E+07	1.22E+07
125	87	160	221	152	58	128	288	169	130	209	155
125	87	160	221	152	58	128	288	169	130	209	155
8.50E+06	5.92E+06	1.09E+07	1.50E+07	1.03E+07	3.94E+06	8.70E+06	1.96E+07	1.15E+07	8.84E+06	1.42E+07	1.05E+07
8.85E+06	6.27E+06	1.12E+07	1.54E+07	1.07E+07	4.30E+06	9.06E+06	1.99E+07	1.18E+07	9.19E+06	1.46E+07	1.09E+07
1.42E+07	1.54E+07	1.25E+07	1.29E+07	1.43E+07	1.29E+07	1.21E+07	1.03E+07	1.24E+07	1.23E+07	1.16E+07	1.22E+07
-5320230.074	-9099945.382	-1223133.579	2504480.395	-3583246.278	-8596902.224	-3019096.747	9642121.084	-520099.0308	-3060430.71	2968661.766	-1340727.378
-5.22E-01	-8.92E-01	-1.20E-01	2.46E-01	-3.51E-01	-8.43E-01	-2.96E-01	9.45E-01	-5.10E-02	-3.00E-01	2.91E-01	-1.31E-01
-23.29541416	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
4.675121831	3.782970323	3.663055266	3.90859256	3.557293905	2.714460354	2.418470477	3.363776465	3.312786364	3.012744138	3.303789409	3.172345549
11.84501988		12.36709889	6.493000957	14.89727499	35.06075708	42.14185462	19.52687882	20.74673769	27.92478139	20.96197586	24.10656582
0.50		0.52	0.27	0.62	1.47	1.76	0.82	0.87	1.17	0.88	1.01

F. CHLORIDE MASS BALANCE CALCULATIONS FOR QUATERNARY GROUNDWATER LENSES

1. Uley South

Current Conditions

Cl mass balance as calculated by Evans (1997):

Average annual rainfall (P) = 570 mm/y
Summer (Nov-April) = 140 mm
Winter (May-Oct) = 430 mm

Average [Cl] rain (C_P) = 14 mg/L

Average [Cl] GW (C_R) = 115 mg/L
(from Fig. 4.6, TDS = 2.0045[Cl-]+340, therefore, this corresponds to a TDS of 571 mg/L)

$$\mathrm{Re}ch\arg e = \frac{PC_P}{C_R}$$

$$= \frac{570x14}{115}$$

= 69 mm/y

If we assume that all incident rainfall evaporates in summer and all recharge occurs in winter, this implies a winter ET of 361 mm.

Scenario: 10% increase in summer rainfall and 10% reduction in winter rainfall. Current ET conditions maintained (i.e. all summer rain evaporates and winter ET requirement is 361 mm).

Summer rainfall = 154 mm
Winter rainfall = 387 mm
Total Rainfall = 541 mm/y

Winter recharge = 387-361 = 26 mm

$$C_R = \frac{PC_P}{R}$$

$$= \frac{541x14}{26}$$

= 291 mg/L

(from Fig. 4.6, TDS = 2.0045[Cl-]+340, therefore, this corresponds to a TDS of 923 mg/L)

2. Uley Wanilla

Current Conditions

Cl mass balance as calculated by Evans (1997):

Average annual rainfall (P) = 570 mm/y
Summer (Nov-April) = 140 mm
Winter (May-Oct) = 430 mm

Average [Cl] rain (C_P) = 8 mg/L

Average [Cl] GW (C_R) = 140 mg/L
(from Fig. 4.6, TDS = 2.0045[Cl-]+340, therefore, this corresponds to a TDS of 621 mg/L)

$$Recharge = \frac{PC_P}{C_R}$$

$$= \frac{570x8}{140}$$

= 33 mm/y

If we assume that all incident rainfall evaporates in summer and all recharge occurs in winter, this implies a winter ET of 397 mm.

Scenario: 10% increase in summer rainfall and 10% reduction in winter rainfall. Current ET conditions maintained (i.e. all summer rain evaporates and winter ET requirement is 361 mm).

Summer rainfall = 154 mm
Winter rainfall = 387 mm
Total Rainfall = 541 mm/y

Winter recharge = 387-397 = 0 mm

Under this climate change scenario, there would be no recharge to the Uley Wanilla Lens.

3. Uley East (Calculations for fresher eastern half of the lens, i.e. discounting the effects from Big Swamp)

Current Conditions

Cl mass balance as in Appendix C:

Average annual rainfall (P) = 570 mm/y
Summer (Nov-April) = 140 mm
Winter (May-Oct) = 430 mm
Average [Cl] rain (C_P) = 8 mg/L
Average [Cl] GW (C_R) = 93 mg/L
(from Fig. 4.6, TDS = 2.0045[Cl-]+340, therefore, this corresponds to a TDS of 526 mg/L)

$$\text{Recharge} = \frac{PC_P}{C_R}$$

$$= \frac{570x8}{93}$$

= 49 mm/y

If we assume that all incident rainfall evaporates in summer and all recharge occurs in winter, this implies a winter ET of 381 mm.

Scenario: 10% increase in summer rainfall and 10% reduction in winter rainfall. Current ET conditions maintained (i.e. all summer rain evaporates and winter ET requirement is 361 mm).

Summer rainfall = 154 mm
Winter rainfall = 387 mm
Total Rainfall = 541 mm/y

Winter recharge = 387-381 = 6 mm

$$C_R = \frac{PC_P}{R}$$

$$= \frac{541x8}{6}$$

= 721 mg/L

(from Fig. 4.6, TDS = 2.0045[Cl-]+340, therefore, this corresponds to a TDS of 1785 mg/L)

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	356 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)

GLOSSARY

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

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

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

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.)

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

Bore. *See well.*

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

CFC (Chlorofluorocarbon). Stable, synthetic, halogenated alkanes, developed in the early 1930s as safe alternatives to ammonia and sulfur dioxide in refrigeration. Uses of CFC-11 and CFC-12 include coolants in airconditioning and refrigeration, blowing agents in foams, insulation and packing materials, propellants in aerosol cans and solvents. Release of CFCs into the atmosphere and subsequent incorporation into the hydrological cycle have closely followed in production. This and their short lifetime make them excellent tracers for young groundwaters 950 year time scale).

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.

EP. Eyre Peninsula.

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

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

Groundwater. *See underground water.*

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

Indigenous species. A species that occurs naturally in a region.

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

ML. *See megalitre.*

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.)*

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.

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

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.)*

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

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.

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

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.

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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