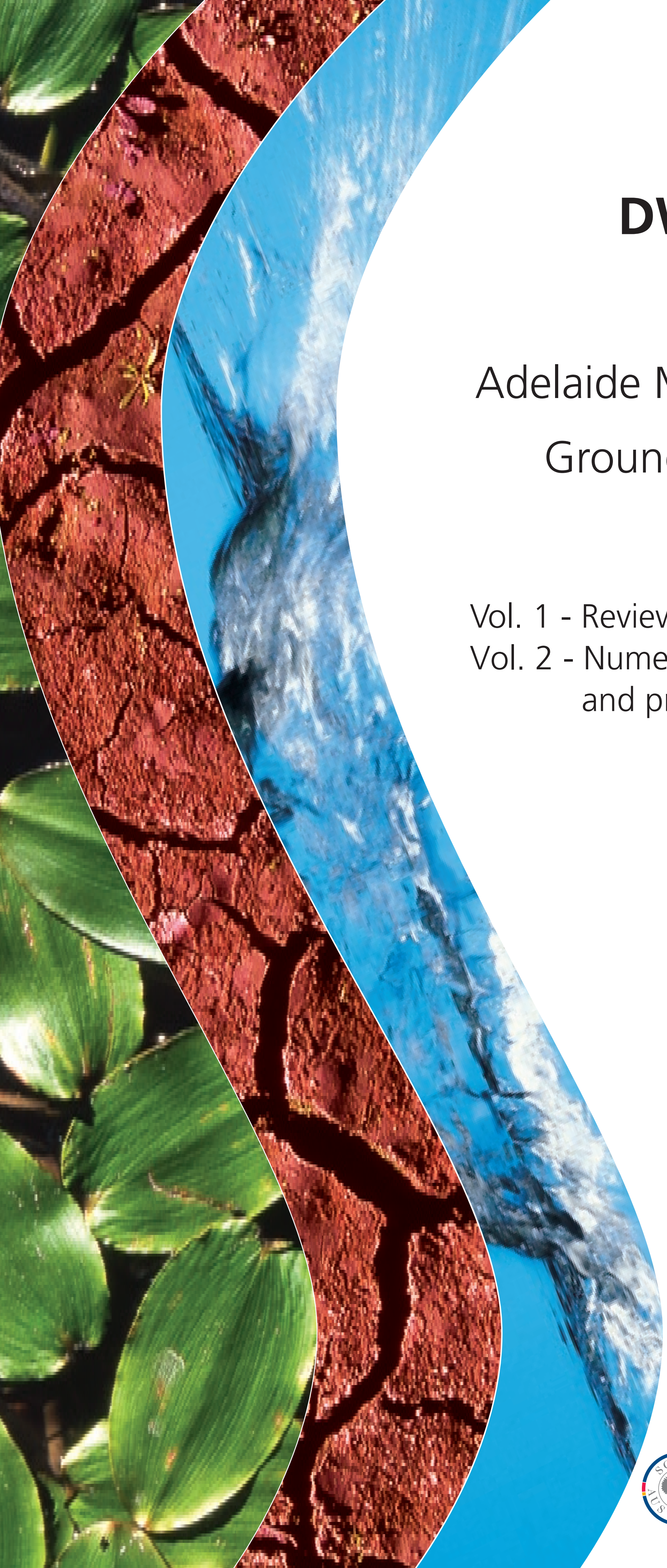

DWLBC REPORT

Adelaide Metropolitan Area Groundwater Modelling Project

Vol. 1 - Review of Hydrogeology
Vol. 2 - Numerical model development and prediction run

2008/05

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

Adelaide Metropolitan Area Groundwater Modelling Project

Volume 1

Review of Hydrogeology

Volume 2

Numerical model development and prediction run

Hajrudin Zulfic, Kwadwo Osei-Bonsu and Steve Barnett

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

July 2008

Report DWLBC 2008/05

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

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ISBN 978-1-921218-86-6

Preferred way to cite this publication
Zulfic, H., Osei-Bonsu, K. and Barnett, S.R., 2008. *Adelaide Metropolitan Area Groundwater Modelling Project. Volume 1 - Review of Hydrogeology, and Volume 2 - Numerical model development and prediction run.* South Australia. Department of Water, Land and Biodiversity Conservation. DWLBC Report 2008/05.

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.

Scott Ashby
CHIEF EXECUTIVE
DEPARTMENT OF WATER, LAND AND BIODIVERSITY CONSERVATION

Adelaide Metropolitan Area Groundwater Modelling Project

Volume 1

Review of Hydrogeology

Hajrudin Zulfic and Steve Barnett

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EXECUTIVE SUMMARY

As part of a project to develop a numerical groundwater model of the sedimentary aquifers beneath the Adelaide Metropolitan Area, a review of the hydrogeology and the current status of the groundwater resources was carried out. Although much of the hydrogeological framework developed over the last decade or so, is robust and is still relevant, recent investigations have provided new information which has prompted revision of the framework in some areas. These include ;

- The Carisbrooke Sand, which is present over large areas of the Adelaide Plains Sub-basin should be named the Carisbrooke Sand Aquifer rather than the Q4 and/or Q5 aquifer. It may be hydraulically connected to the underlying T1 aquifer in the Little Para River area only.
- In Zone 2A (the Para Fault splinter block), there is continuous flow within the Tertiary aquifers across the fault zone, with no inter-aquifer flow resulting from the vertical displacement of the sediments due to faulting (ie there is no flow from the T2 to T1 aquifer as previously thought).
- In Zone 4 (Golden Grove Embayment) where the Tertiary sediments lens out against rising shallow basement in the vicinity of the River Torrens, the hydrostratigraphic units should keep their assigned names from where they were developed in the deepest portion of the embayment (ie the T3 aquifer should not be renamed the T1 aquifer because it is the first Tertiary aquifer intersected near the Torrens).

Examination of potentiometric surface contours for the T1 aquifer show only a slight expansion of the cone of depression in the West Lakes – Grange area from 1997 to 2007, indicating a new equilibrium has been established, with extractions currently approximating 8000 ML/yr. Hydrographs show slight declines in some areas in response to some increases in extraction.

Data gaps identified include the true thickness of the T2 aquifer, and more accurate estimates of recharge volumes (from the Mt Lofty Ranges) and discharge volumes (from beneath Gulf St Vincent). The spatial distribution of salinity data for the T2a aquifer in the Golden Grove Embayment is also inadequate.

A review of the existing monitoring network is recommended. It would be beneficial to monitor water level fluctuations on a quarterly basis because of the continuous nature of industrial groundwater abstractions. Salinity monitoring and regular reviews of sampling trends are necessary in order to enable more vigorous management of the resource. Compulsory annual sampling of each licensed well should be stipulated in the Water Allocation Plan.

1. INTRODUCTION

The deep Tertiary aquifer systems beneath the greater urban area of Adelaide (Fig. 1) are experiencing increasing demand pressure as drought and increasing costs for reticulated water make groundwater a more economically attractive option for water supply.

Groundwater from these aquifers is used mainly by industries that require continuous supplies of water, and also by large irrigation users, such as schools and golf courses. The increasing demand resulted in the prescription of the Central Adelaide Prescribed Wells Area in June 2007 (shown in red in Fig. 1).

The objectives of the current project are to review the hydrogeology of the sedimentary aquifers beneath the Adelaide Metropolitan Area, and to develop a numerical groundwater model that has the capacity to determine the long term risks to the aquifer system, and to test various management scenarios.

This report examines the current status of the resource and with the benefit of new information from recent investigations, reviews the hydrogeological framework of the aquifer systems.

The scope of this study included extensive data compilation and reinterpretation of existing hydrogeologic and hydraulic data from recent investigations and several published and unpublished documents. In addition, a literature review of previous hydrogeologic and groundwater modelling studies in the Adelaide Metropolitan Area and in the neighbouring Northern Adelaide Plains was carried out.

Figure 1. Adelaide Metropolitan Area locality map

2. PREVIOUS WORK

The geology, groundwater resources and recharge mechanisms of the Adelaide Plains area were first comprehensively described by Miles (1952). Steel (1962) later described the subsurface stratigraphy in the western suburbs of Adelaide, where palaeontological studies were carried out on five bores in the western suburbs of Adelaide and provided new information on the stratigraphy and structure of this part of the Adelaide Plains Basin.

Lindsay and Shepherd (1966) investigated the hydrogeologicaly important Munno Para Clay Member, which is forming the confining bed between the two main Tertiary aquifers occurring in the Adelaide Plains. Lindsay (1969) later carried out palaeontological studies of many samples from 93 bores in order to better understand the subsurface stratigraphy of the Adelaide Plains Sub-Basin of the St Vincent Basin.

Gravimetric investigation of the Eden-Burnside Fault zone from Burnside to Brighton was carried out by Coppin (1967), with additional work by Hough (1986) in the Clapham-Panorama area. Another gravity survey examined the Para Fault west of the Adelaide city area (Finlayson, 1978). This survey indicates the fault zone comprises one major fault with a maximum throw of 650 m, with smaller nearly parallel or en-echelon faults on either side.

Shepherd (1975) presented a summary of the hydrogeology of the Adelaide Plains sub-basin, with data on salinity and groundwater use from the two main Tertiary aquifers.

Investigations at North Glenelg provided hydrogeological information for the Tertiary aquifers in this area (Gerges, 1980), through cable tool drilling and testing of a new observation well. Rotary drilling was carried out at Allenby Gardens (Gerges, 1982) to provide hydrogeological information on the full sequence of the Tertiary aquifers and underlying formations. The hole was geophysically logged with extensive side wall coring. Discharge tests were carried out to enable calculation of approximate values of hydraulic conductivity and transmissivity.

In the study ‘The Cainozoic St Vincent Basin-tectonics, structure, stratigraphy’, Cooper (1985) provided information on tectonics, structure and stratigraphy of the St Vincent Basin.

Gerges (1986) summarised the stratigraphy, hydrogeology and underground water resources of the Adelaide Metropolitan area with the latest understanding of recharge mechanisms at that time.

As part of the ongoing investigations in the Adelaide Metropolitan Area, Edwards et al (1987) conducted a survey of groundwater extractions. The survey was conducted between January 1982 and April 1984 for the 1982–83 and 1983–84 irrigation seasons.

Dighton (1994) analysed 25 groundwater samples from fractured rock (Adelaide Hills) and sedimentary aquifers, for chemistry and stable isotopes analysis (^{2}H and ^{1}8O), as well as carbon isotopic composition of dissolved inorganic carbon (^{13}C and ^{1}4C). Although the main purpose was for field testing a new direct absorption method for carbon – 14 analysis, the results were also used to evaluate the existing conceptual model regarding recharge processes within the Adelaide Metropolitan Area.

In 1996, Gerges completed an overview of the hydrogeology of the Adelaide metropolitan area (Gerges, 1996), but later in 1999, he completed the most comprehensive study of the geology and hydrogeology of the Adelaide metropolitan area that established the current conceptual understanding of the major aquifer systems in the area (Gerges, 1999). He compiled historical pumping data and water levels for the major aquifer systems, and constructed a comprehensive, medium complexity groundwater numerical flow model.

A review of the groundwater resources of the Northern Adelaide Plains area was completed in 2001 (Gerges, 2001).

Hodgkin (2004) carried out an assessment of the storage capacities of the sedimentary aquifer systems to determine the aquifer storage and recovery (ASR) potential of the Adelaide region, which includes the Adelaide Plains Sub-basin and Golden Grove Embayment.

In a supporting document for the prescription of the Adelaide Plains Tertiary confined aquifers under the *Natural Resources Management Act 2004*, Martin and Hodgkin (2005) summarised the status and condition of the aquifers.

AGT (2005) constructed two production wells at the Glenelg Golf Club, and a subsequent aquifer test provided information for a revision of the hydrostratigraphy of the area.

3. PHYSICAL SETTING

3.1 BOUNDARIES AND TOPOGRAPHY

The Adelaide Metropolitan Area occupies about 560 km^2 of coastal plain and forms part of the sedimentary St Vincent Basin. The area is bounded to the east by the Mt Lofty Ranges (the Adelaide Hills) and to the west by St Vincent's Gulf. The study area is divided into two sub-areas, the Golden Grove Embayment and Adelaide Plains Sub-basin (Gerges, 1996) with seven major physiographic features (Fig. 2).

1. The Eden Fault Block forms the major escarpment in the background to the City of Adelaide and its suburbs. The scarp rises rapidly up to 300 m above sea level, and is the source of most streams flowing across the area including the Torrens and Sturt Rivers.
2. The Para Fault Block occurs in the area north of the Torrens River and is bounded to the west by the Para Fault.
3. The Burnside Splinter Block is a narrow zone between the Eden and Para Fault Blocks with heights of 120–150 m above sea level.
4. The Upper Outwash Plain is bounded by the River Torrens to the north, the Burnside Fault to the east and south and the Para Fault to the west. It descends from an elevation of 160 m to less than 30 m above sea level.
5. The Lower Outwash Plain extends from the Para Fault to the coast with a low surface gradient of 3 m/km.
6. Coastal sand dunes extend along entire coast from Burnside Fault to Port Adelaide. Immediately behind the sand dunes lies an estuarine plain area, which extends from Glenelg to Port Adelaide.

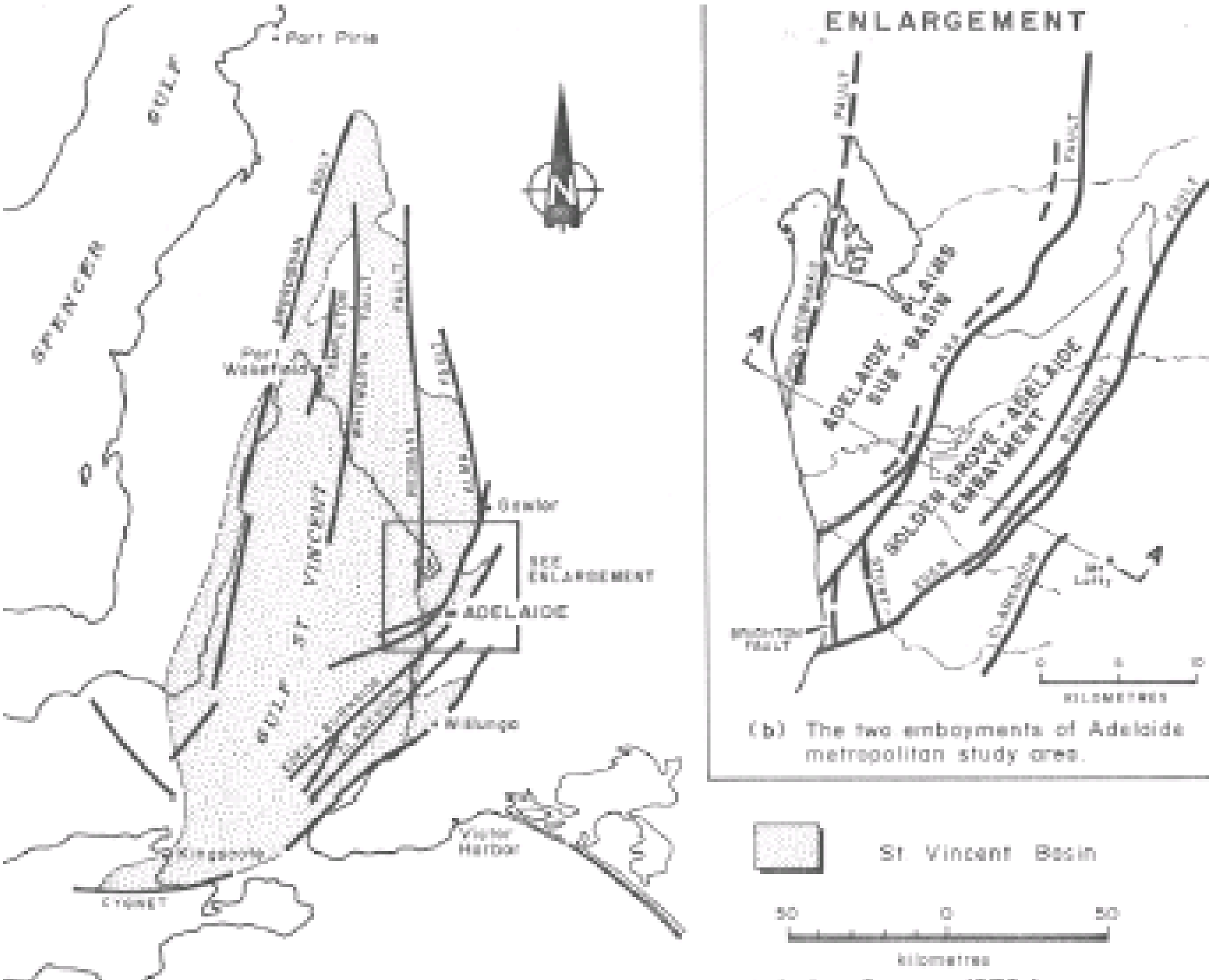
3.2 SURFACE HYDROLOGY

Several ephemeral watercourses, including the River Torrens and the Sturt River, flow in a westerly and northwesterly direction towards Gulf St Vincent. Six smaller creeks flow from the hills across the plains and discharge into the River Torrens from the south, while Brownhill Creek discharges into the Sturt River. Sixth Creek flows northeasterly before discharging into the Torrens River gorge.

During the early days of settlement, water supplies were obtained from these watercourses and as demand increased, shallow wells were dug adjacent to them. The streams flow during all winter months but in summer the flows decrease dramatically in the major streams, and cease completely in the smaller streams.

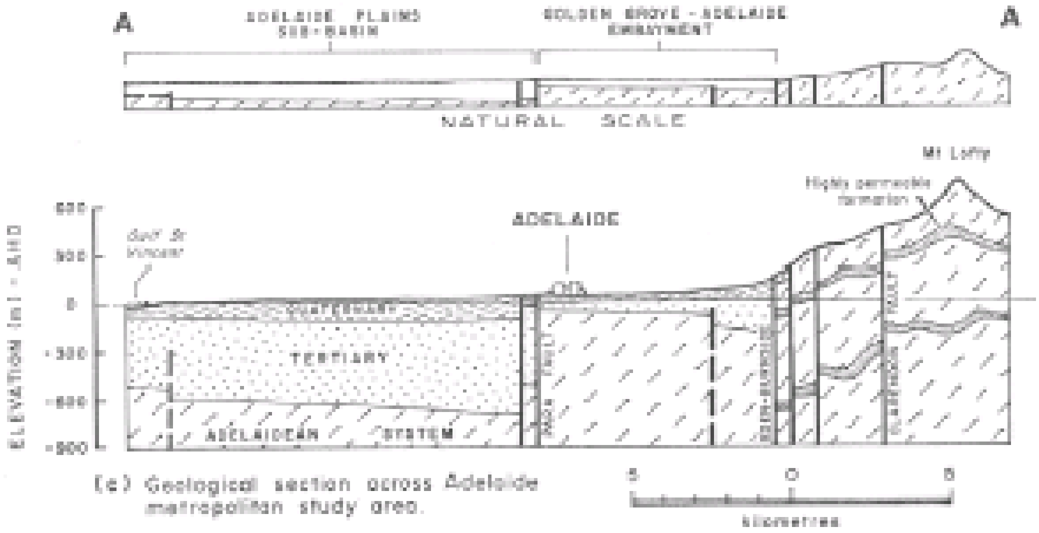
3.3 CLIMATE

The Adelaide area has a typical Mediterranean-type climate; hot, dry summers and cool, wet winters. The average annual precipitation at Adelaide City is 531 mm with 60–65% of annual rainfall occurring during the period from May to September. The lowest rainfall occurs in January and February and accounts for only 3–4% of the yearly average, while June and July have the highest average, each 14% of total average annual rainfall.



(a) St Vincent Basin and tectonic framework (after Cooper, 1979)

(b) The two embayments of Adelaide metropolitan study area.



(c) Geological section across Adelaide metropolitan study area.

Figure 2. Physiographic features of the Adelaide Metropolitan area

4. GEOLOGY

4.1 STRATIGRAPHY

The Adelaide Metropolitan Area is part of the St Vincent Basin, an intracratonic sedimentary basin formed by rejuvenated Palaeozoic faults during the continental separation of Australia and Antarctica in the Eocene (Cooper, 1979). Basin sediments are up to 700 m thick and were laid down in a shallow graben bounded by folded and block-faulted Proterozoic and Palaeozoic (Drexel and Priess, 1995).

The St Vincent Basin has been subdivided into several sub-basins, the largest being the Adelaide Plains Sub-basin (Fig. 2). The Golden Grove Embayment is asymmetric tectonic valley in which the wedge of sediments dips gently southwards and thickens towards its faulted southeastern margin. It is bounded by the Eden-Burnside and Para Faults.

Gerges (1999) examined around 800 well logs and delineated stratigraphy and hydrogeology of the Adelaide Plains Sub-basin and Golden Grove Embayment based on correlation with logs previously described by Lindsay and Cooper. Tables 1–3 summarise the stratigraphy of the area as determined by Gerges (1999).

Table 1. Summary of Precambrian stratigraphic units

Unit name	Lithology
Wilmington Formation	Siltstone, sandstone, pebbly limestone
Brighton limestone	Limestone
Tapley Hill Formation	Dark laminated siltstone; basal Tindelpina Shale Member, black shale, dolomite
Sturt Tillite	Bouldery sandy siltstone and quartzite
Mitcham Quartzite	Siltstone, sandstone and quartzite at base
Saddleworth Formation and Beaumont Dolomite	Slate, dolomite and quartzite
Stonyfell Quartzite	Feldspathic quartzite, arkose and siltstone
Woolshed Flat Shale	Laminated siltstone, phyllite and quartzite
Balhannah Shale Member	Black slate
Skillogalee Dolomite	Dark chert, sandstone, phyllite and grey dolomitic rock
Aldinga Sandstone	Feldspathic sandstone, arkose and conglomerate
Barossa Complex	Schist and micaceous gneiss

Table 2. Summary of Quaternary stratigraphic sequence

Unit name and age	Thickness (m)	Lithology and occurrence	Environment of deposition
St Kilda Formation	4	Sand and silt, numerous shell remains adjacent to coast	Marine
Pooraka Formation	4	Clay—light brown, gravelly and sandy in basal deposits	Alluvial
Glanville Formation	6	Highly fossiliferous limestone adjacent to northwest coast	Marine
Keswick Clay	5	Mainly green clay with minor sand. Occurs in isolated areas	Non-marine
Hindmarsh Clay	16	Clay—mottled, brown, pale olive-grey, with thin layers of gravel, sand. Green-grey clay 3–5 m thick at the base	Fluviatile, estuarine
Carisbrook Sand	20	Yellow fine sand with thin layers of clay and silt. Occasionally carbonaceous. Occurs in vicinity of large palaeo-rivers and adjacent to fault zones	Fluviatile, estuarine

Table 3. Summary of Tertiary stratigraphic sequence

Unit name and age	Average thickness (m)	Lithology and occurrence	Environment of deposition
Burnham Limestone	2	Limestone—white and clayey. Occurs in association with Hallett Cove Sandstone.	Marine
Hallett Cove Sandstone and Dry Creek Sand	50	Shelly dark grey to brownish-grey sand, silt and clay. Highly fossiliferous sandstone. Occurs over whole area west of Para Fault in a restricted area between Brown Hill Creek and the coast.	Marine, warm shallow environment
‘Croydon facies’	10–45	Fossiliferous sand and silt, glauconitic. Thin shelly and sandstone interbeds occur over whole area west of Para Fault.	Shallow marine
Port Willunga Formation – upper unit	35	Yellow fossiliferous sand, limestone grading to white hard limestone. Occurs over area west of Para Fault and west of Sturt River as a thin strip along the coast.	Shallow warm marine shelves
Munno Para Clay Member (Port Willunga Formation)	12	Dark grey, stiff, calcareous clay. Comprises beds of clay separated by two bands of white to grey limestone.	Warm marine
Janjukian unit (Port Willunga Formation)	20	Sand, pale grey to yellow, silty, occasional limestone-environmental bands. Glauconitic. Occurs west of Para Fault and in Golden Grove-Adelaide Embayment possibly south of River Torrens.	Warm marine
Ruwarung Member (Port Willunga Formation)	78	Pale grey interbedded chert-limestone and siltstone. Glauconitic, pyritic. Occurs over the whole area except north of River Torrens in Golden Grove-Adelaide Embayment.	Marine
Aldinga Member (Port Willunga Formation)	36	Clay, stiff, grey to dark grey, carbonaceous. Glauconitic, pyritic. Shell remains grading to sand and silt. Occurrence similar to overlying member. Change to sandy silty facies in an area near Eden-Burnside fault zone.	Marginal marine
Chinaman Gully Formation	12	Grey to black carbonaceous silt and clay. Highly pyritic, lignitic. Sand at the base.	Marginal marine
Blanche Point Formation	50–70	Grey, friable shelly siltstone grading to alternating hard and soft siltstone bands (cherty). Glauconitic, large *Turritella* shells. Moderately cemented greenish to pale grey, highly glauconitic limestone at the base.	Deep marine
Tortachilla Limestone	3–5	Brown and green, weakly cemented glauconitic limestone.	Marine
South Maslin Sand	20	Dark grey carbonaceous sand and silt. Pyritic and glauconitic.	Marginal marine
Clinton Formation	16	Pale grey, white clay, sandy. Pyritic. Highly carbonaceous, lignite layers.	Marine to non-marine
North Maslin Sand	15	Pale grey, yellow and brown, clayey, silty and gravely pyritic sand.	Fluviatile, estuarine

4.2 STRUCTURE

The boundary between the plains and the Mt Lofty Ranges, formed by uplifted blocks of Precambrian rocks, reflects the importance of geological structure in the formation of the Adelaide Plains (Taylor et al, 1975). Two major fault zones, the Eden-Burnside Fault and the Para Fault, control the topography of the area as shown in Figures 2 and 3 (Gerges, 1999). These faults are responsible for most of the major dislocation and tilting of the Precambrian rock and for forming two embayments.

The Eden-Burnside Fault forms the scarp face of the Adelaide Hills, while on its downthrow side, thick Tertiary to Recent sediments have been deposited. Lindsay (1969) indicated that the Eden-Burnside Fault comprises at least of three faults. Coppin (1967) used the gravimetric method to delineate the Eden-Burnside Fault zone with some accuracy from Burnside to Brighton, and concluded that the results agreed well with the structure derived solely from geological considerations.

Miles (1952) originally proposed the location of the Para Fault, which trends south southwesterly in the Adelaide area and then westerly towards the gulf, and forms the eastern boundary of the Adelaide Plains Sub-basin. A gravity survey conducted by Finlayson (1978) indicates that the Para Fault zone comprises one major fault with a maximum throw of 650 m, with smaller nearly parallel faults on either side.

On the basis of stratigraphy and the gravity survey results, Gerges (1980a) identified new locations of the northern and southern splinters of the Para Fault, and located the Para Fault East. He also suggested an extension of the Para Fault West northward, and located the previously unrecognised Brighton Fault and “extended” the Hope Valley Fault southwards to near the Brown Hill Creek.

5. REVIEW OF HYDROGEOLOGY

Gerges (1999) divided the study area into a number of major zones, each of which contains complex but reasonably consistent hydrogeological characteristics. Interconnections between the aquifers are controlled by major structures and or changes in lithological facies, which strongly affect the groundwater flow regime.

Zone 1 covers the basement rocks of the Adelaide Hills and contains fractured rock aquifers. The Adelaide Hills form the south and southeastern boundaries of the sedimentary basin and receive an annual rainfall of up to 1100 mm/y, which is almost double that recorded on the plains.

Zone 2 covers the area between Brown Hill Creek and St Vincent Gulf. It contains between two and four Quaternary aquifers and between three and four Tertiary aquifers. Only the first Tertiary aquifer has significant development.

Zone 2A is hydrogeologically important as it is highly faulted and connects Zone 2 with Zone 3. Limited information is available for deep aquifers and therefore interpretation of major structures is speculative. It includes up to four Quaternary aquifers and possibly three or four Tertiary aquifers.

Zone 3 contains five to six Quaternary aquifers and also three to four Tertiary aquifers. The first and second Tertiary aquifers are the thickest and the most productive, with relatively low salinities. The greatest fraction of abstracted groundwater for industrial and recreational use comes from the first Tertiary aquifer.

Zone 4 covers a large portion of the Golden Grove Embayment. It contains up to three Quaternary and three Tertiary aquifers, and a fractured rock aquifer. Each Tertiary aquifer consists mainly of thin layers of fine sand with low yields. Most of the Quaternary and Tertiary aquifers are thin, shallow and locally interconnected in the vicinity of the River Torrens. The shallow fractured rock aquifer near the River Torrens contains groundwater of low salinity and significant yield.

Zone 4A is located between the Eden-Burnside Fault and the anticipated extension of the Hope Valley Fault. It contains up to five Quaternary aquifers, one thick undifferentiated Tertiary aquifer (up to 130 m thick) and also the fractured rock aquifer.

The extent of these zones is presented in Figure 3. They will be often be referred to in the following hydrogeological review.

5.1 QUATERNARY AQUIFERS

The main lithology of the Quaternary sediments is mottled clay and silt with interbedded sand and gravel (with thin consolidated layers). The sands and gravels form up to six thin confined aquifers within the Hindmarsh Clay, which are designated Q1 to Q6 in order of increasing depth (Table 5).

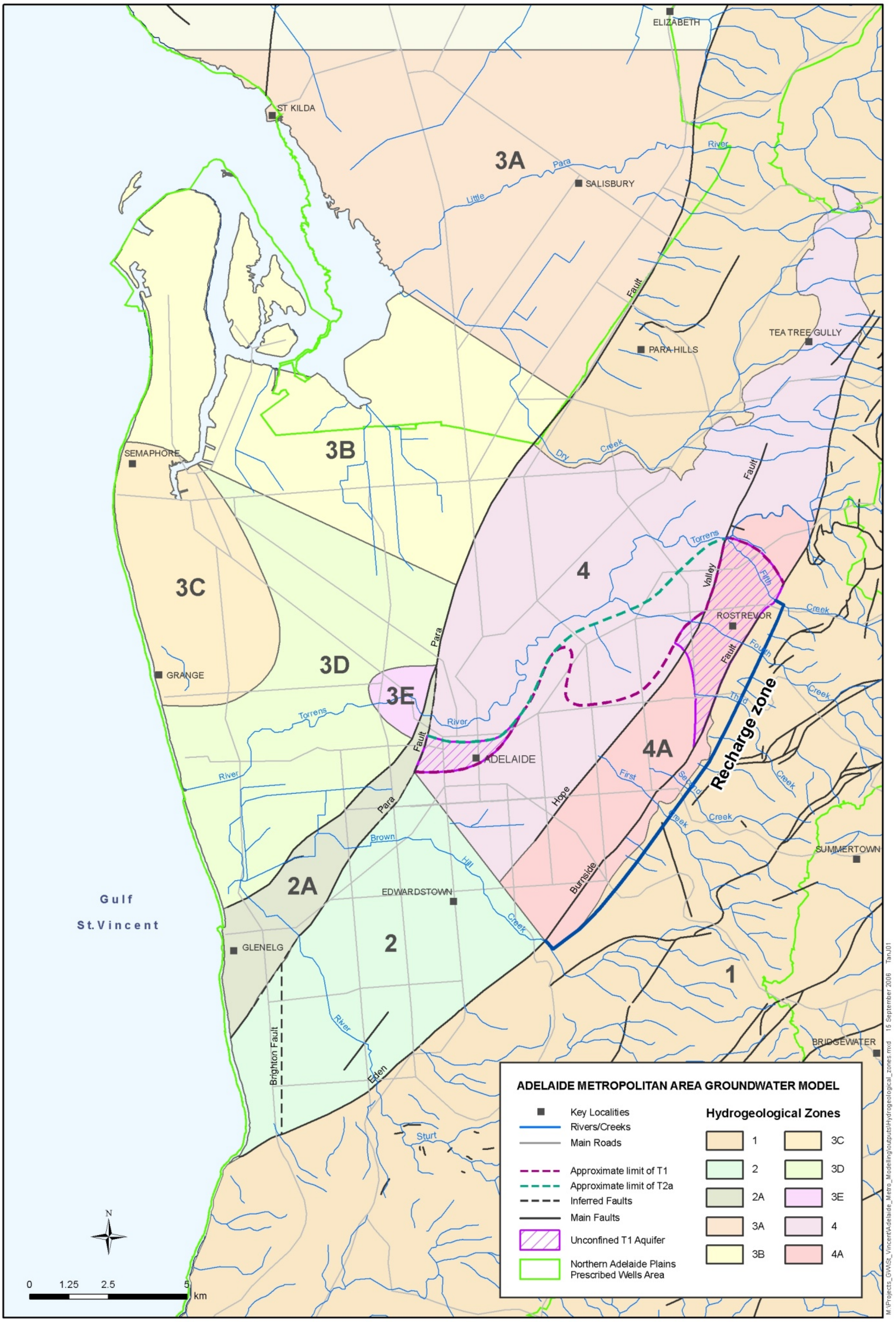


Figure 3. Adelaide Metropolitan Area hydrogeological zones

The Quaternary aquifers vary greatly in thickness, lithology and hydraulic conductivity. Generally, the grain size decreases towards the coast, and with increasing distance from surface drainage and major structures such as the Para Fault.

The confining layers between the Quaternary aquifers consist of clay and silt and range in thickness from 1–20 m. These confining layers are absent in some areas, allowing hydraulic connection between aquifers.

Gerges (1999) described Quaternary aquifers in detail and the following brief description is sourced from this report.

5.1.1 FIRST QUATERNARY AQUIFER (Q1)

This aquifer is well distributed over the Adelaide Metropolitan Area and is located at depths between 3–10 m below ground level with average thickness of 2 m. In the proximity of major structures and surface drainage, aquifer materials tend to be coarser and thicker and therefore more transmissive.

This aquifer was previously regarded as unconfined, but careful examination of water cut data has revealed that, in the majority of wells, confined conditions exist. Average supplies from this aquifer rarely exceed 2 L/s, from wells mostly located along major drainage lines and major structures.

The direction of groundwater flow is northwesterly to westerly over the Para Fault Block, and northerly to northwesterly and westerly over the Adelaide Plains Block. The potentiometric surface gradient is steep in the east adjacent to the Mt Lofty Ranges. Near the coast and west of the Para Fault, the gradient is almost flat which may be a result of higher transmissivity and/or the effect of flat topography.

Heavy pumping from the underlying Tertiary aquifer has induced downward leakage, which has led to the development of a cone of depression in the Q1 aquifer in the northern part of the area, and may induce seawater intrusion into the Q1 aquifer in this area.

In general, the outflow from the Q1 aquifer to the ocean is small, as the gradient at the coast is flat and the transmissivity is relatively low.

5.1.2 SECOND QUATERNARY AQUIFER (Q2)

This aquifer is well distributed over most of the area except along the River Torrens upstream of Thebarton, where it merges with the first Quaternary aquifer.

The top of the aquifer lies between 16–30 m below ground. Its thickness ranges from 0.5–10 m with an average thickness of 2 m. In general, the aquifer is thicker near major surface drainage lines, and available information suggests that 4 m of gravel can supply up to 6 L/s west of the Para Fault. The grain size of aquifer material, and hence available yield, decreases towards the coast and with increasing distance from surface drainage.

This aquifer shows a very wide range in salinity, from less than 500 mg/L to almost 30 000 mg/L. The lowest salinities are found adjacent to streams (First Creek to Fifth Creek) and fractured rock aquifers of the Mt Lofty Ranges, and also along the northern side of the River Torrens. The limited information suggests that the flow direction is similar to that of the first Quaternary aquifer, ie towards the northwest.

5.1.3 THIRD QUATERNARY AQUIFER (Q3)

This aquifer is widely distributed throughout the area, except along the River Torrens to the east of the City of Adelaide, where it merges with other aquifers. Depth to the Q3 aquifer is between 30 and 45 m below ground. The aquifer dips gently to the northwest, similar to the overlying Q2 aquifer.

The Q3 aquifer consists of gravel and sand with an average thickness of 2 m. Adjacent to major surface drainage features, yields of up to 3.5 L/s are common.

Low salinities in the area adjacent to the Eden-Burnside Fault indicate that recharge is dominated by lateral flow from the fractured rock aquifer. In the area west of the Para Fault, the extent of lower salinity zones in the Q3 aquifer is much greater than in the overlying Q2 aquifer, suggesting that downward leakage may not be the dominant recharge mechanism.

Regional flow is towards the northwest, similar to the general flow directions of the two overlying Quaternary aquifers.

5.1.4 FOURTH QUATERNARY AQUIFER (Q4)

This aquifer, which is located at depths between 45–60 m below ground, is well developed near major structures and in areas west of the Para Fault. In the area between the Eden-Burnside Fault and the Para Fault, the aquifer merges with underlying and/or overlying aquifers. It consists mainly of gravel and sand and/or sandstone. Average yield is about 1.2 L/s, however exceptionally high yields of up to 9 L/s have been recorded.

Low salinities of about 700 mg/L are found near the Eden-Burnside Fault and west of the Para Fault, suggesting direct recharge from the fractured rock aquifer or another Tertiary aquifer respectively. Also salinities of 1000 mg/L are recorded along the northern side of the River Torrens. Further towards the west, the salinity increases dramatically to more than 20 000 mg/L.

Several recorded salinity values are significantly lower than the overlying Quaternary aquifer, indicating that downward leakage is not the prime mechanism responsible for flushing of this system, and that most of the recharge occurs as a result of lateral flow from adjacent aquifer(s). The salinity distribution over the whole area suggests a flow direction towards the west and northwest.

5.1.5 FIFTH QUATERNARY AQUIFER (Q5)

The distribution of this aquifer is restricted to west of the Para Fault, apart from a small area in proximity to the Eden-Burnside Fault. The depth to the Q5 aquifer is between 65–80 m below ground. Aquifer thickness averages 2 m and yields rarely exceed 0.7 L/s.

Salinities of up to 1900 mg/L along the River Torrens in proximity to the Para Fault indicates that recharge from surface water drainage does not reach the Q5 aquifer in this area. The zone of less than 1500 mg/L salinity immediately west of the Para Fault indicates that lower salinity groundwater flows across the Para Fault from aquifers to the southwest (Zone 2a). Generally, flow is towards the north to northwest.

The pre-development water level elevation ranges between 9 m in the eastern area and 2 m near the coast, indicating a groundwater flow direction towards the west-northwest. This flow direction is similar to the general flow direction deduced from present day water level elevations and salinity distributions within the aquifer, and from the overlying Quaternary aquifers.

The pre-development general hydraulic gradient can be estimated at 1 x 10^{-3} m/m, and the present day gradient at 0.85 x 10^{-3} m/m, indicating a slightly flatter gradient in response to downward leakage.

5.1.6 SIXTH QUATERNARY AQUIFER (Q6)

The distribution of this aquifer is limited to the area west of the Para Fault. The depth to the top of the aquifer is 80–100 m below ground with an average thickness of 2 m. The Q6 aquifer generally consists of sand and gravel with low yields (up to 2.5 L/s).

The salinity of the aquifer ranges from less than 700 mg/L in several areas, to 45 000 mg/L near the Gulf. Salinities of up to 1375 mg/L have been recorded near the River Torrens in proximity to the Para Fault, which indicates that surface water does not influence recharge to this deep Quaternary aquifer. There are obvious similarities in salinity distribution between the Q6 and Q5 aquifers, in particular the extent of the less than 1000 mg/L zone, which dominates the area centred on the River Torrens.

In some wells, salinity values in the Q6 aquifer are lower than those in Q5, suggesting recharge from the better quality water in the underlying first Tertiary aquifer.

Major Quaternary aquifer characteristics are summarised in Table 4. The average thickness of all aquifers is about two metres.

Table 4. Summary of the Quaternary aquifers

Aquifer		**Thickness** (m)	**Yield** (L/s)	**Salinity** (mg/L)	**Range of depths** (m) **in Zone 3**	**Location in Zones**
First	Q1	0.5–10	2	1000–21 000	3–15	2, 2A, 3, 4 and 4A
Second	Q2	0.5–10	6	500–29 300	16–30	2, 2A, 3, part of 4 and 4A
Third	Q3		3.5	1000–>5000	31–45	2, 2A, 3, part of 4 and 4A
Fourth	Q4		1.2–8.8	700–20 000	46–60	2A, 3 and part of 4A and 2
Fifth	Q5	<12	0.7–11.5	<1000–75 000	65–80	3 and part of 4A and 2
Sixth	Q6		1–2.5	700–45 500	90	Part of 3

5.1.7 CARISBROOKE SAND AQUIFER

The Carisbrooke Sand lies beneath the Hindmarsh Clay. It is a confined aquifer that extends throughout most of the Adelaide Plains Sub-basin, but it is absent in the western and northwestern metropolitan suburbs. Gerges (1999) describes this aquifer as the Q4 aquifer in the Northern Adelaide Plains area and the Q4/Q5 aquifer in the Metropolitan area. The hydraulic character of the Carisbrooke Sand is different from the Hindmarsh Clay Quaternary aquifers and will be referred to as the Carisbrooke Sand aquifer in this report.

The depth to the Carisbrooke Sand aquifer ranges between 60–80 m below ground. The aquifer averages about 20 m in thickness, except near the Little Para River where it is 40–60 m thick. The aquifer consists of multi-coloured, poorly sorted, fine to medium grained quartz sand and silt, with some clay and thin gravel beds. Wells within the aquifer are typically low yielding and require screening and extensive development to minimise the production of sand. The potential supply is about 4 L/s. Salinities vary from 600 near the Little Para River, to 3600 mg/L in the Wingfield area.

Gerges (2001) describes the Carisbrooke Sand aquifer as the Q4 aquifer, which may be included as a part of the T1a aquifer along the Little Para River. However, Hodgkin (2004) suggested that this aquifer is in direct hydraulic connection with the underlying T1 aquifer over much of its extent.

The hydrographs of monitoring wells completed in the T1 and Carisbrooke Sand aquifers in the Little Para River area (Fig. 4) display very different trends (although only 50 m apart), suggesting that either the T1 and Carisbrooke Sand aquifers are not directly hydraulically connected, or the performance of the Carisbrooke Sand monitoring well is impeded by clogging of the production zone of the well.

It has been decided to include the Carisbrooke Sand Aquifer as a part of T1 Aquifer in the Little Para River area, but for the current groundwater modelling exercise, the Carisbrooke Sand Aquifer is deemed to constitute a separate aquifer and is coupled with rest of Quaternary sediments in one layer.

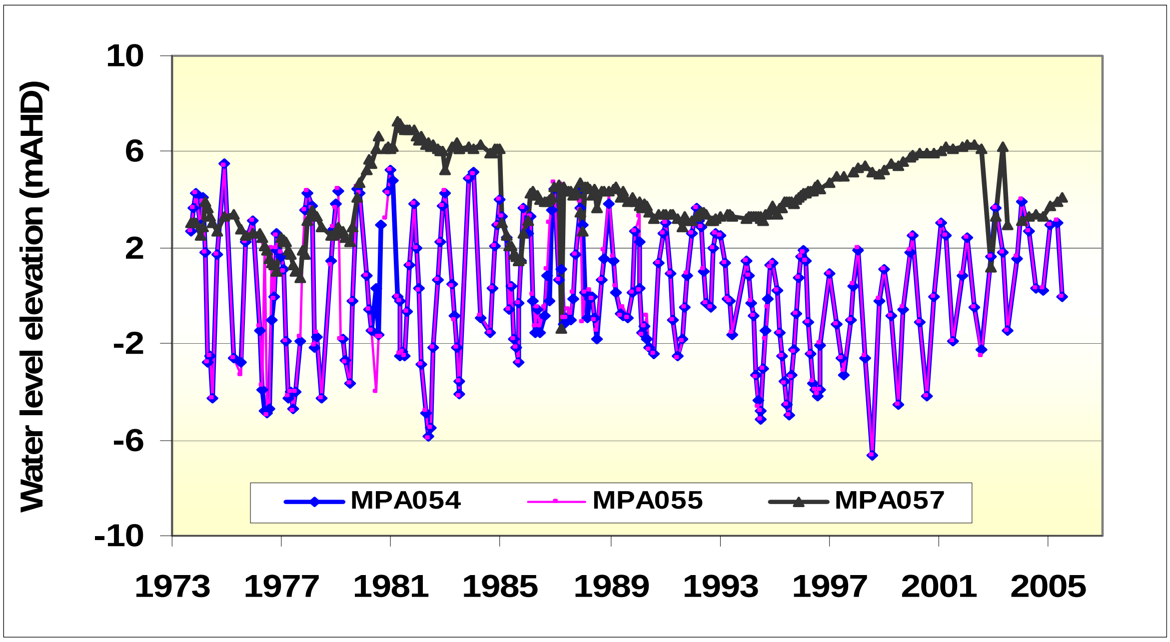


Figure 4. T1 and Carisbrooke Sand aquifer hydrographs in the Little Para River area

5.2 TERTIARY AQUIFERS

The main source of groundwater supply in the study area is from the Tertiary sediments that contain several aquifer systems, each of which comprise various sub-aquifers. Groundwater occurs mainly in four mostly confined Tertiary aquifers, designated T1 to T4 in order of increasing depth (Gerges 1999). These aquifers are relatively independent of the hydrogeological units (Table 5), and could consist of different units in different zones.

The distribution of the Tertiary aquifers depends largely on the depositional environment, major structural features, movements along the major faults and the general geological history of the area. Table 6 summarises the aquifer distributions within zones.

Table 5. Hydrogeological units

Unit	Unit name	Hydrogeological properties	Maximum Thickness (m)
1	Quaternary (including Hindmarsh Clay)	Confining bed; up to six thin confined aquifers	Various
2	Blue to brown clay	Confining bed	10
3	Carisbrooke Sand	Aquifer	60
4	Hallett Cove Sandstone and Dry Creek Sand	Confined Aquifer	48
5	‘Croydon facies’	Semi-confining bed	?40
6	Upper Port Willunga Formation	Confined aquifer	47
7	Munno Para Clay Member	Confining bed	12
8	Lower Port Willunga Formation	Confined aquifer	110
9	Ruwarung Member	Confining bed	70
10	Aldinga Member – clay	Confining bed	49
11	Aldinga Member – sand	Confined aquifer	20
12	Chinaman Gully Formation – lignite, clay	Not known	18
13	Chinaman Gully Formation sand	Confined aquifer	30
14	Blanche Point Formation	Confining bed	105
15	Tortachilla Limestone/South Maslin Sand	Confined aquifer	5 / 60 -100
16	Clinton Formation	Confining bed	38
17	Undifferentiated Tertiary sand	Confined aquifer	125
18	Weathered Precambrian – clay	Confined bed	55
19	Unweathered Precambrian (basement)	Aquifer (fractured rock)	Not known

Table 6. Tertiary aquifer distributions in each zone

Zone	Aquifer presence confirmed	Comment
2	T1 to T4	T4 aquifer is well developed only near the coast.
2A	T1 and T2	T3 and T4 aquifers are anticipated at greater depth.
3	T1 to T4	All four aquifers are well developed in this zone
4	T1 and T2a	The T1 and T2a aquifers are relatively thin in this zone
	T2b and T3[1]	T2b - Chinaman Gully Formation (Tandanya Sand) and T3 - Maslin Sand
4A	Only one thick sandy aquifer (T1) containing several stratigraphic units.	

The hydrostratigraphy of the Golden Grove Embayment is complex as a result of erosional and depositional boundaries, lateral facies changes and faulting. Several geological units thus often form a single aquifer system. A significant portion of the T1 aquifer occurs as semi-confined or unconfined sandy aquifers in the northern and northeastern areas of the embayment (Hodgkin, 2004). It is thought the Tertiary aquifer north of the Torrens River is not in hydraulic continuity with the T1 or T2a aquifers south of the river.

The hydrostratigraphy of the Adelaide Plains Sub-basin, which includes the area west of the Para Fault, uses the same nomenclature as the Golden Grove Embayment but is less complex because of the greater aquifer continuity and uniformity. The major fault systems are considered to be transmissive in many areas, permitting significant lateral groundwater throughflow from fractured rock aquifers in the Adelaide Hills westwards into the adjoining Tertiary aquifers (Gerges, 1999).

Gerges (1996) contains detailed cross-sections which are not reproduced in this report.

5.2.1 FIRST TERTIARY AQUIFER (T1)

Within the Golden Grove Embayment (Zones 2, 2A, 4 and 4A) as within the Adelaide Plains Sub-basin (Zone 3), the T1 aquifer is defined as the shallowest Tertiary aquifer system present. Within the embayment, the T1 aquifer can consist of any of several Tertiary formations.

Within **Zone 2** in the area between Brown Hill creek and east of Sturt River, the T1 aquifer can consist of the sandy facies of the Hallett Cove Sandstone, Dry Creek Sand or Ruwarung Member, limestone facies of the Lower Port Willunga Formation and possibly the Carisbrooke Sand which is hydraulically connected to the underlying Port Willunga Formation limestone in proximity to the hills. The T1 aquifer has an average thickness of 50 m, which increases to 80 m near the Adelaide Hills.

Gerges (1999) suggests the base of the aquifer is generally located in the middle of Ruwarung Member, except near the Eden-Burnside Fault where it is located inside the Aldinga Member. This aquifer could supply an average 15 L/s, except near the Adelaide Hills and along Sturt River where the yields are lower.

Several kilometres either side of the Sturt River, the T1 aquifer is represented by the T1a sub-aquifer, which consists of the Hallett Cove Sandstone and Dry Creek Sand with the Munno Para Clay at the base. The T1a sub-aquifer has an average thickness of 3 m and is low yielding. It is suggested that this thin aquifer should be coupled with Quaternary sediments.

Most of the production wells in this zone are completed in the T1 aquifer which consists of limestone of the Lower Port Willunga Formation.

Along a narrow strip (~1.5 km) along the coast in Zone 2, the T1 aquifer comprises two major sub-aquifers—T1a (which consists of Carisbrooke Sand, Hallett Cove Sandstone, Dry Creek Sand and permeable portion of Croydon Facies sediments), and the T1b sub-aquifer which consists mainly of the Upper Port Willunga Formation which overlies the Munno Para Clay. The average thickness of the T1 aquifer in this zone ranges from 25–50 m (the T1a averaging 30 m and the T1b, 20 m). Supplies range up to 6 L/s.

Within **Zone 2A**, the T1 aquifer has similar characteristics to those in the coastal zone of the Zone 2 and the same hydrostratigraphy as throughout the Adelaide Plains Sub-basin (Zone 3), which is described in the following section. The aquifer thickness in this region ranges from about 10–55 m (average 25 m). In this zone, the T1 aquifer can supply up to 20 L/s. Gerges (1996) found that low salinity groundwater below 1000 mg/L in Zones 2 and 2a is restricted to an area between Brownhill Creek and Sturt River, and is generally lower than that salinity found under both drainage lines. He concluded that the recharge mechanism is more complex than the simple downward infiltration from surface drainage as it was proposed by Miles (1952).

Prior to significant groundwater development, most wells had pressure levels above ground level. These historical artesian conditions for the T1 aquifer in Zone 2a suggests that upward leakage from the T1 aquifer into overlying Quaternary aquifers was an important component of the flow system, and again supports the conclusion that infiltration of surface water along drainage lines does not recharge the T1 aquifer.

Zone 3 comprises the Adelaide Plains Sub-basin. The hydrostratigraphy of the T1 aquifer in this zone is relatively simple, and comprises the Carisbrooke Sand, Hallett Cove Sandstone, Dry Creek Sand and Croydon Facies as the T1a sub-aquifer, and the Upper Port Willunga

Formation as the T1b sub-aquifer. A semi-confining bed consisting of part of the Croydon Facies separates the T1a and T1b sub-aquifers.

The total thickness of the T1a aquifer (Hallett Cove Sandstone, Dry Creek Sand and the upper portion of the Croydon Facies), can be up to 70 m. These units are well distributed over the whole area. The depth to the top of the T1a aquifer varies between 60–130 m below ground, averaging 110 m.

The T1b sub-aquifer consists of limestone and sand of the upper Port Willunga Formation which is well distributed over the whole of Zone 3. The aquifer attains a maximum thickness of 60 m and often supports high yielding bores with open-hole production intervals, making it a preferred aquifer for industrial and horticultural users and ASR projects.

A grey Quaternary clay separates the T1 aquifer from the overlying Quaternary aquifers. It is uniformly distributed over the area and has maximum thickness of 13 m.

The Munno Para Clay, which forms the base of the T1 aquifer, acts as a confining layer between the T1 and T2 aquifers. It is a dark grey clay 6–10 m thick, and is usually interbedded with two beds of pale grey limestone. The clay is of a very low permeability, with a vertical hydraulic conductivity averaging 1.6 x 10–5 m/d.

Groundwater salinity ranges from 700 mg/L in the middle of the zone, increasing to 900 mg/L towards the south and up to ~3000 mg/L in the Zone 3B. The extent of groundwater salinity below 800 mg/L in the T1 aquifer is much greater than in the overlying Quaternary aquifers, confirming that recharge to the T1 aquifer is lateral.

Within **Zone 4**, which covers a large portion of Golden Grove Embayment, Gerges (1999) suggested the T1 aquifer is typically about 25 m thick and consists of the shallowest aquifer present which varies across the zone, and could either be the sandy lithologies of the Carisbrooke Sand, Aldinga Member, Chinaman Gully Formation, South Maslin Sand or undifferentiated sands.

Selby and Lindsay (1982) previously differentiated four Tertiary aquifers in the city area of Zone 4. Figure 5 is a cross-section from this report along King William Street from Barton Terrace in the north, to Greenhill Road in the south.

It shows the Tertiary sediments lensing out in the vicinity of the River Torrens, including the Carisbrooke Sand aquifer and the Hallett Cove Sandstone (in yellow), the Aldinga Sand Member (in blue), the underlying Tandanya Sand Member (in green), and the South Maslin Sand (in red). It is now proposed that in Zone 4, these hydrostratigraphic units should keep their assigned names from the deepest portion of the embayment where they were developed, even though these aquifers might be only locally interconnected in the vicinity of the river. Based on Selby and Lindsay's interpretation and new information, the following framework has been adopted:

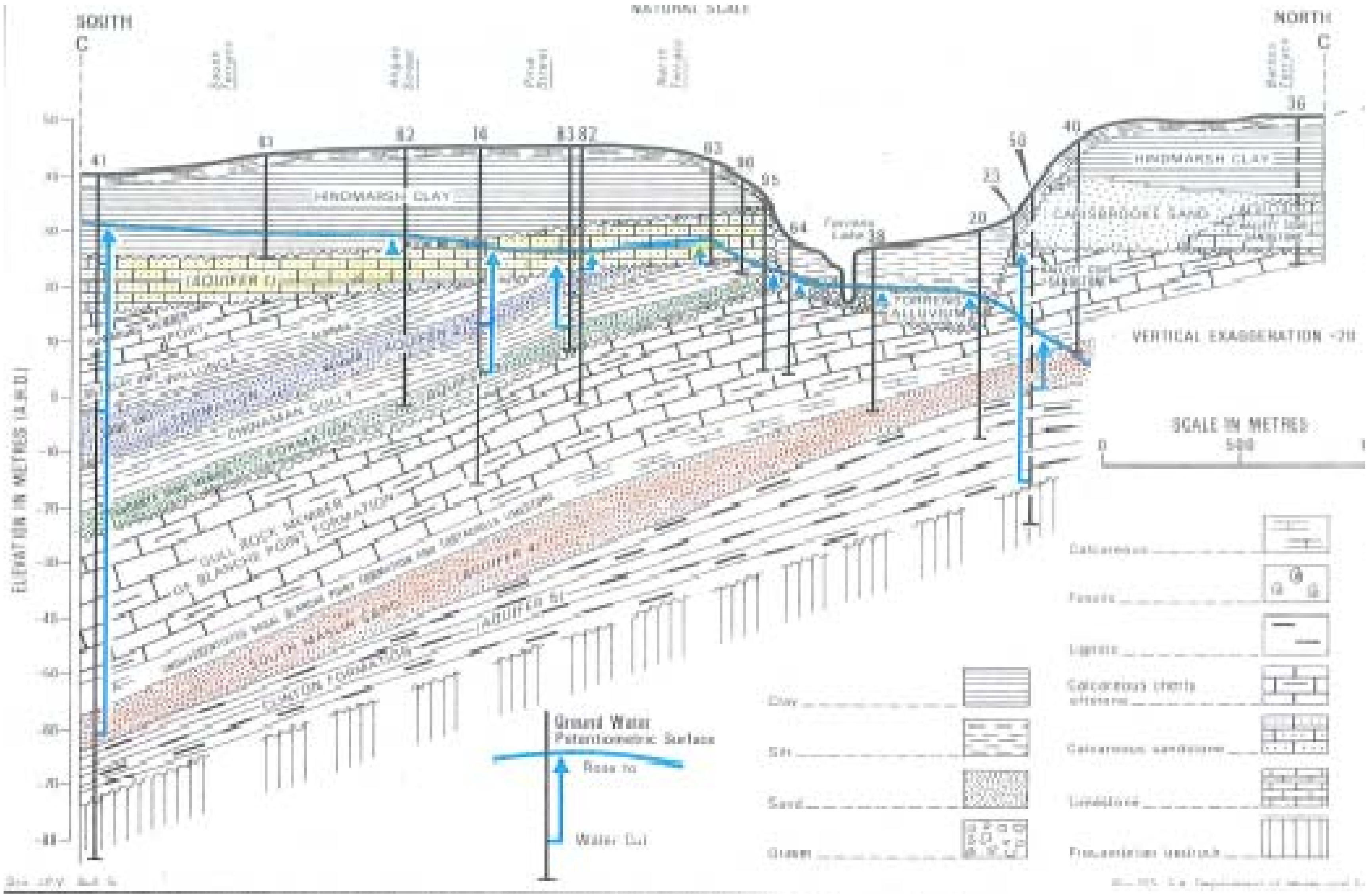


Figure 5. North – south cross section through Adelaide city

1. The T1 aquifer in Zone 4 consists of the Carisbrooke Sand, Hallett Cove Sandstone/Dry Creek Sand and sand layers of the Ruwarung Member.
2. The Aldinga Sand Member should be considered part of the T2a aquifer in Zone 4, as it is clearly a continuation of the T2a aquifer from Zone 2.
3. The Chinaman Gully Formation (Tandanya Sand) aquifer should be considered as part of the T2b aquifer in the embayment. Over most of the embayment, this aquifer is separated from the overlying T2a aquifer by lignitic clay of Chinaman Gully Formation, and might be only locally connected to the overlying T2a aquifer.
4. Accordingly, the South Maslin Sand would be the T3 aquifer in this zone as it is found in most of Zone 2 (to the east of the Brighton Fault).

The T1 aquifer is predominantly confined, but can be semi-confined or unconfined near the River Torrens and in proximity to the Eden-Burnside Fault. Supplies from this aquifer are very limited and rarely exceed 2 L/s. Low salinities are restricted to small areas, particularly along Fourth Creek. The high salinity of the Q1 aquifer along this creek suggests that the recharge to the T1 aquifer occurs as lateral flow. However, the high salinity of the T1 aquifer along the Torrens River indicates a lack of recharge of fresh water to the aquifer. Gerges (1999) suggests that general groundwater flow is towards the northwest, towards and along the Torrens River, where during the summer, the outflow of high salinity groundwater significantly increases river salinity. The T1 aquifer in this zone is hydraulically connected to the Quaternary aquifers west of Para Fault in Zone 3.

However, any outflow of high salinity groundwater from Tertiary aquifers would occur as local outflow, as the T1 or T2a aquifers pinch out south and southeast of the Torrens River, and their connection to the alluvium aquifer would not be of a regional character. The deeper Tertiary aquifers, T2b (Tandanya Sand) and T3 (Maslin Sand), which are becoming shallower in this area, could be discharging into Torrens alluvium from the southern and southeastern side, causing an increase in salinity of the river during summer period.

Within **Zone 4A**, which is located between the Eden-Burnside Fault and the extension of the Hope Valley Fault, Gerges (1999) recognised a deeply buried Tertiary trough containing up to 130 m of clastic sediments. This trough extends along most of the length of the downthrown side of the Eden-Burnside Fault and contains one thick Tertiary aquifer, which consists of various stratigraphic units including undifferentiated Tertiary sand. This trough has great hydrogeological significance as a major zone of recharge for the Golden Grove Embayment and the Adelaide Plains Sub-basin. The best groundwater quality below 800 mg/L occurs near the Eden-Burnside Fault zone, which is the result of direct lateral flow from the Fractured Rock Aquifer of Zone 1 to the T1 aquifer. In certain areas, the aquifer is unconfined, particularly to the south and north of the Torrens River, and near the Eden-Burnside Fault zone.

The general groundwater flow direction in this zone is towards the northwest and into Zones 2 and 4, with groundwater discharge also occurring to the Torrens River. Depending on the nature of the bounding faults, the T1 aquifer in the Golden Grove Embayment can be hydraulically connected to fractured rock aquifers along the hills face zone and to Quaternary or Tertiary aquifers west of the Para Fault. A summary of the T1 aquifer information and hydraulic parameters are presented in Tables 7 and 8.

Table 7. Summary of T1 aquifer information

Zone	Equivalent hydrogeologic units	Average thickness (m)	Main lithological description
4A	3, 10, 11, 12, 13, 14, 15, 16 and 17	120	Fine to medium sand with occasional thin gravel beds and thin clayey and lignitic layers.
4	3, 4 and 9[1]	25	Fine sand, silty and clayey.
2	4 (thin), 6 (near the coast), mainly Unit 8 and part of 9	50+	Some thin sandstone, limestone grading downwards to course sand and silt. Sandstone, sand and limestone.
2A	4, 6, 8 and part of 9	25	Sandstone, sand and limestone.
3	4, part of 5 and 6[1]	80	Sand, sandstone, shells and silty sand and limestone.

Table 8. T1 aquifer parameter values (after Gerges, 1999)

Zone	Transmissivity (m^2/d)	Storage coefficient	Thickness (m)	Hydraulic conductivity (m/d)	Remarks
2	200	5.5×10^{-4}	50	3.5	Bailey Reserve
3	120–175	2.5 x 10-4	60–80	2.5	Kidman Park and Grange golf course aquifer tests and flow net analyses
4A	130–360	–	120	2–3	Hazelwood Park pump test
4	? 25–40 (estimated)	–	25	1.0	

Hodgkin (2004) reviewed a number of aquifer tests conducted in both the T1 and T2 aquifers, and found that hydraulic conductivity values in the T1 aquifer are in the range 1–19 m/d. Aquifer test locations with the spatial distribution of hydraulic conductivity results are presented in Figure 6.

5.2.1.1 T1 aquifer salinity distribution

Gerges (1999) examined water quality data from several hundred wells and shows the predevelopment salinity distributions within the T1 aquifer in Figure 7. Major findings are summarised below:

The extent of groundwater salinity below 800 mg/L in the T1 aquifer is much greater than in any of the overlying Quaternary aquifers.

The T1 aquifer salinity from individual wells is much less than the overlying Quaternary aquifers, even in areas under surface drainage, implying that recharge to the T1 aquifer did not occur as a result of downward leakage.

The T1 aquifer is hydraulically continuous across the Para Fault splinters with groundwater flow towards the northwest.

The higher groundwater salinity in Zone 4 suggests no flow from this zone into Zone 3.

Two flow mechanisms to the Tertiary aquifers were inferred from the distribution of low salinity groundwater:

- Flow to the west in the Little Para River area (Zone 3A)
- Flow towards the northwest in Golden Grove Embayment and southern part of Adelaide Plains Sub-basin (Zones 4A, 4, 2, 2A and 3).

An area of relatively higher salinity over 2500 mg/L, which is located at the far extent of the recharge and flushing fronts in the Adelaide Plains (Zone 3), separates these two major low salinity flow paths.

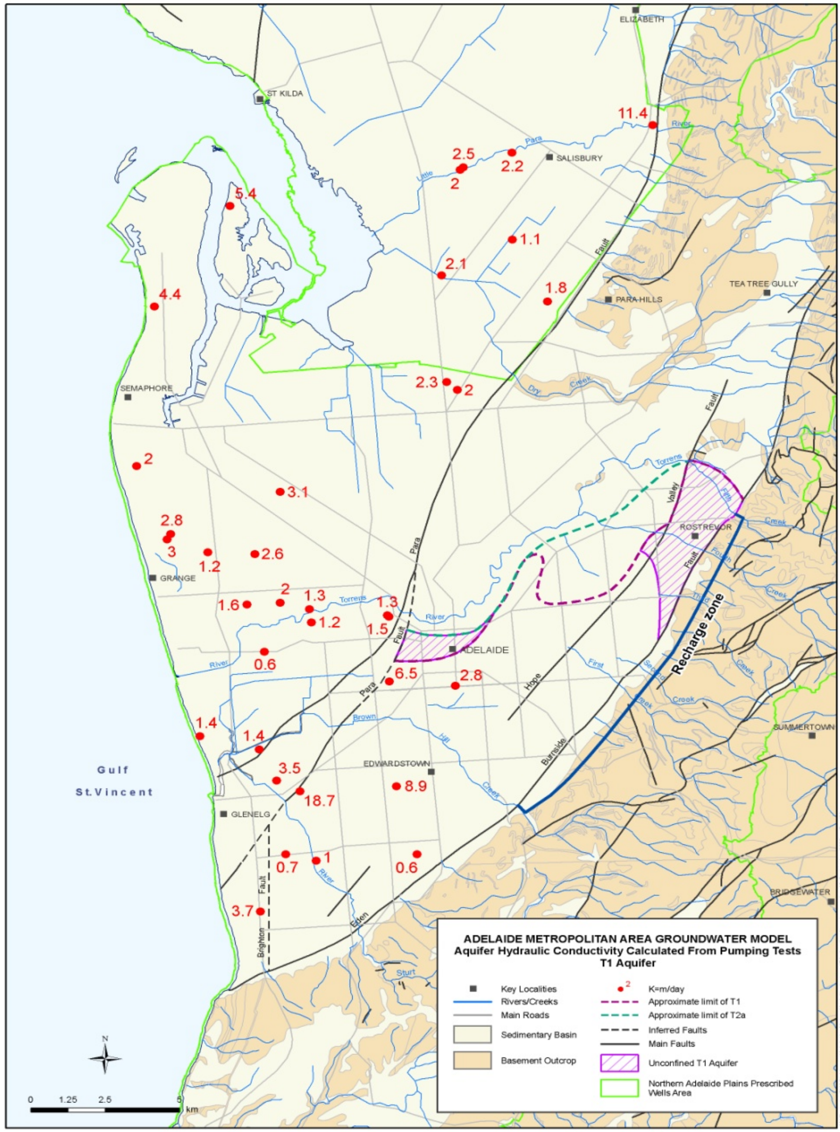


Figure 6 T1 aquifer hydraulic conductivity calculated from aquifer tests

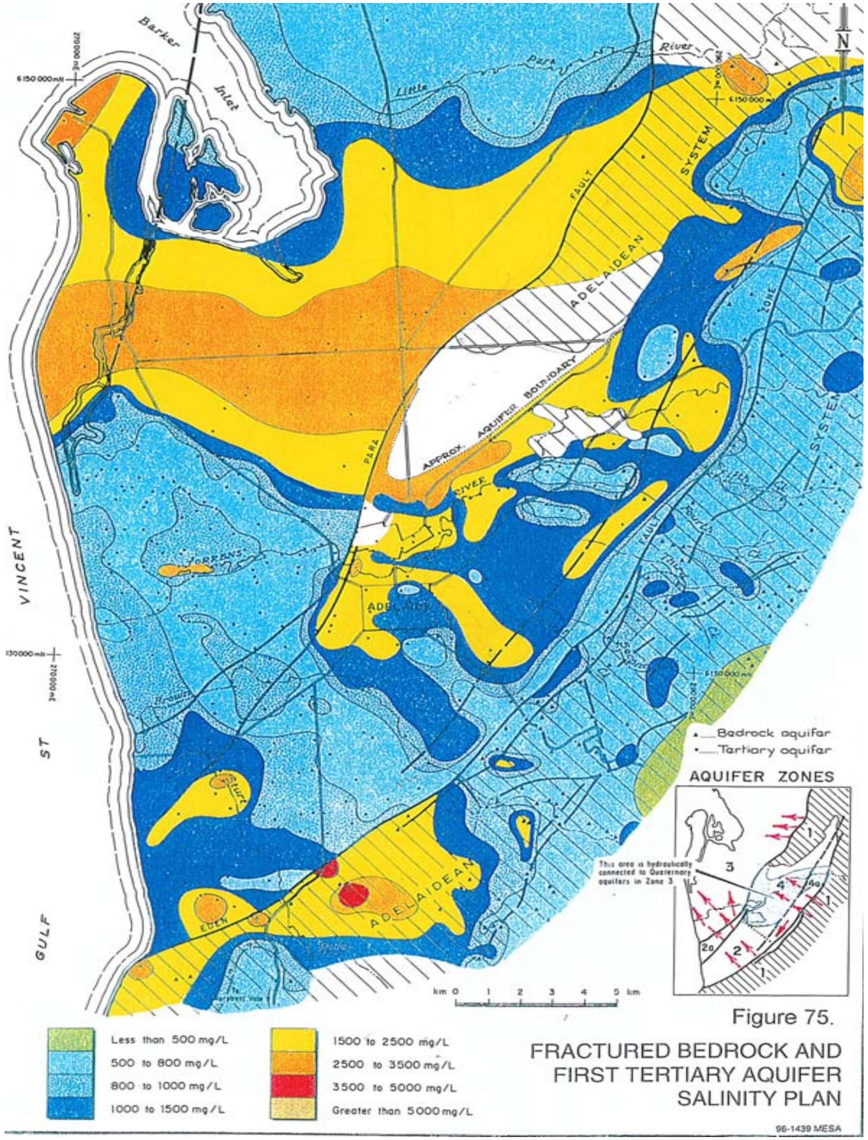


Figure 7 T1 aquifer pre-development salinity map

> Salinity increases in the T1 aquifer of the order of 3–5 mg/L/y have occurred in response to pumping due to lateral inflow near the edges of low salinity areas and/or vertical leakage from adjacent aquifers (downward from the deepest Quaternary aquifer and upward from the T2 aquifer).

Hodgkin (2004) constructed a salinity contour map for the T1 aquifer, but because of a lack of recent salinity information, it is not considered an improvement over previous salinity mapping.

5.2.2 SECOND TERTIARY AQUIFER (T2)

The T2 aquifer is defined as the second Tertiary aquifer, which underlies and is separated from the T1 aquifer by a confining layer. Like the T1 aquifer, it is well distributed throughout the Golden Grove Embayment and can consist of various stratigraphic units (Table 8), but is generally thinner than the T1 aquifer. The T2 aquifer also occurs throughout the entire Adelaide Plains Sub-basin and consists of the well-cemented limestone of the Lower Port Willunga Formation.

Within **Zone 2** (the area between Brown Hill Creek and Sturt River), Gerges (1999) describes the T2 aquifer as a confined aquifer comprising sandy facies of the Aldinga Member and Chinaman Gully Formation. He concluded that the T2 aquifer in this area was not hydraulically connected to the T2 aquifer within the Para Fault splinter to the north (Zone 2A), based on salinity differences between the zones. The estimated supply from this aquifer is about 5 L/s.

As suggested earlier, in Zone 4 the Chinaman Gully Formation (Tandanya Sand member) should be considered as a separate T2b aquifer for the following reasons:

1. The Aldinga Sand Formation (T2a aquifer) and Tandanya Sand member (T2b aquifer) are separated by the lignitic clay of the Chinamen Gully Formation, which acts as a confining layer.
2. Most of the high groundwater salinities were collected from wells completed in the Tandanya Sand member of the Chinaman Gully Formation (unit 13), eg 6628-719, 6628-8135, 6628-12256.
3. The very limited number of salinity records from the Aldinga Sand Member suggests this aquifer has better quality groundwater than the underlying Tandanya Sand.
4. Multiple water cuts from the well 6628-13129 show that groundwater salinity from the Aldinga Sand Member is in the range 1020–1230 mg/L, with salinities of the Chinaman Gully Formation much higher, between 1800–3500 mg/L.

Taking in consideration the limited data available for the Aldinga Sand Member (T2a aquifer), it is not possible to conclude whether this aquifer is hydraulically connected to the T2 aquifer in the adjacent Para Fault block or not. Further investigation in the vicinity of the Para Fault splinter block might be warranted to assess the salinity and yield of this aquifer and its possible hydraulic lateral continuity with the T2 aquifer.

In the area west of the Sturt River near the coast, the dominant stratigraphic unit is the lower limestone of the Port Willunga Formation, which attains thicknesses of up to 95 m. Groundwater salinity in this area ranges from 950–3600 mg/L. Lower groundwater salinity occurs near the coast where supplies of up to 10 L/s can be obtained. The anticipated groundwater flow in this area is towards the west.

In **Zone 2A** (the Para Fault splinter block), the aquifer consists of the Lower Port Willunga Formation, which is up to 70 m thick. It contains the best T2 aquifer water quality in the Metropolitan Area. Gerges (1999) originally suggested the T2 aquifer in this zone is hydraulically connected to the T1 aquifer south of Para Fault splinters (Zone 2) and to the T1 and T2 aquifers north of the Para Fault (Zone 3).

This conclusion assumed that vertical displacement of the Tertiary sediments had occurred due to faulting – a view that was probably influenced by examining cross sections with a very large vertical exaggeration (20 x). In reality, the downwarping of the sediments across the fault zone occurs with a gradient of 1:13, which is relatively low. Figure 8 presents the revised cross section which depicts continuous flow within aquifers across the fault zone with no vertical displacement.

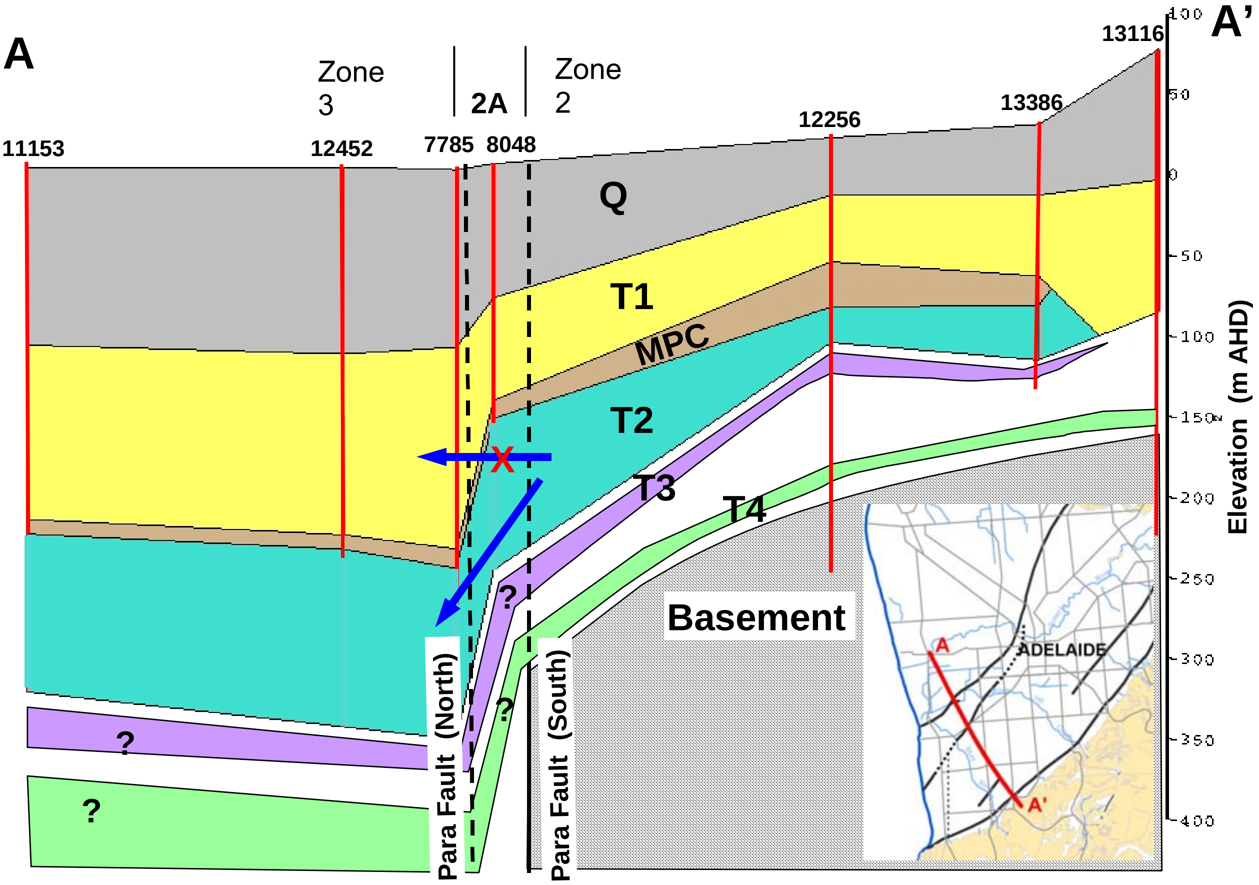


Figure 8. Cross section A – A' from Zone 2 to Zone 3

Recent drilling supports this argument. Two new ASR wells were recently completed for the Glenelg Golf Club developing the T1b aquifer (6628-22322) in Zone 3, and the T2 aquifer (6628-22321) in Zone 2A respectively. During a 24-hour constant discharge pumping test on the T1b aquifer well, the two T1 monitoring wells responded to pumping whilst the T2 well did not respond. This suggests that the T2 aquifer in Zone 2A is not hydraulically connected to either the T1 aquifer north of the Para Fault in Zone 3, or the overlying T1 aquifer in Zone 2A as previously thought (AGT, 2005).

Within **Zone 3**, the T2 aquifer consists of the well-cemented limestone of the Lower Port Willunga Formation that occurs throughout the entire zone. The formation is relatively flat lying and is relatively uniform in thickness, ranging between 80–110 m (Fig. 8).

Based on lithological and salinity characteristics, Gerges (1999) recognises three sub-aquifers within the T2 aquifer in Zone 3.

> T2a — the shallowest sub-aquifer consists of white to pale grey well-cemented limestone with salinities varying from 1200–3600 mg/L.
>
> T2b — consists of orange-brown moderately cemented limestone/sandstone. Salinities range between 5000–8000 mg/L.
>
> T2c — the deepest sub-aquifer consists of pale grey to yellowish brown sandy silt and sandy limestone.

Because of these salinity variations within the T2 aquifer, further development of this essentially unused water resource in Zone 3 should be cautious, and further investigations are recommended.

There are two historic flow mechanisms which have occurred in this aquifer and produced the observed salinity distribution. A northwesterly flowpath occurred from the T1 aquifer in Zone 2 and the T2 aquifer in Zone 2A, through the Para Fault splinter block and into the T2 aquifer in Zone 3. In addition, a westerly flowpath occurred from the fractured rock aquifer into the T2 aquifer in the Little Para River area - a recharge mechanism is very similar to that in the overlying T1 aquifer.

Within **Zone 4**, the T2 aquifer occurs mainly as a confined aquifer comprising sandy beds of the Chinaman Gully Formation and/or South Maslin Sands (Hodgkin, 2004). The aquifer is relatively thin ranging from about 3–15 m in thickness.

After reviewing new information, it is now suggested that the T2a aquifer comprises the Aldinga Sand Member, which is a continuation of the T2a aquifer from Zone 2. The Chinaman Gully Formation (Tandanya Sand) should be considered as a separate T2b aquifer in the GGE, where this aquifer is overlain by the lignitic clay of the Chinaman Gully Formation (unit 12 – confining bed), and might be only locally connected to the overlying T2a aquifer.

Accordingly, the South Maslin Sand would be the T3 aquifer in this zone (as in Zone 2).

Within **Zone 4A**, there is effectively no occurrence of the T2 aquifer.

A summary of the T2 aquifer information and hydraulic parameters are presented in Tables 9 and 10.

Hodgkin (2004) revised a number of pumping tests conducted in both the T1 and T2 aquifers, and found that horizontal conductivity of the T2 aquifer varies between 1–10 m/d. Aquifer test locations with spatial distribution of hydraulic conductivity results are presented in Figure 9.

5.2.2.1 T2 aquifer salinity disributuion

Figure 10 presents the salinity distribution for the T2 aquifer. Major conclusions for the T2 aquifer groundwater salinity in Zones 2A and 3 are drawn from the Gerges (1999) study and they are:

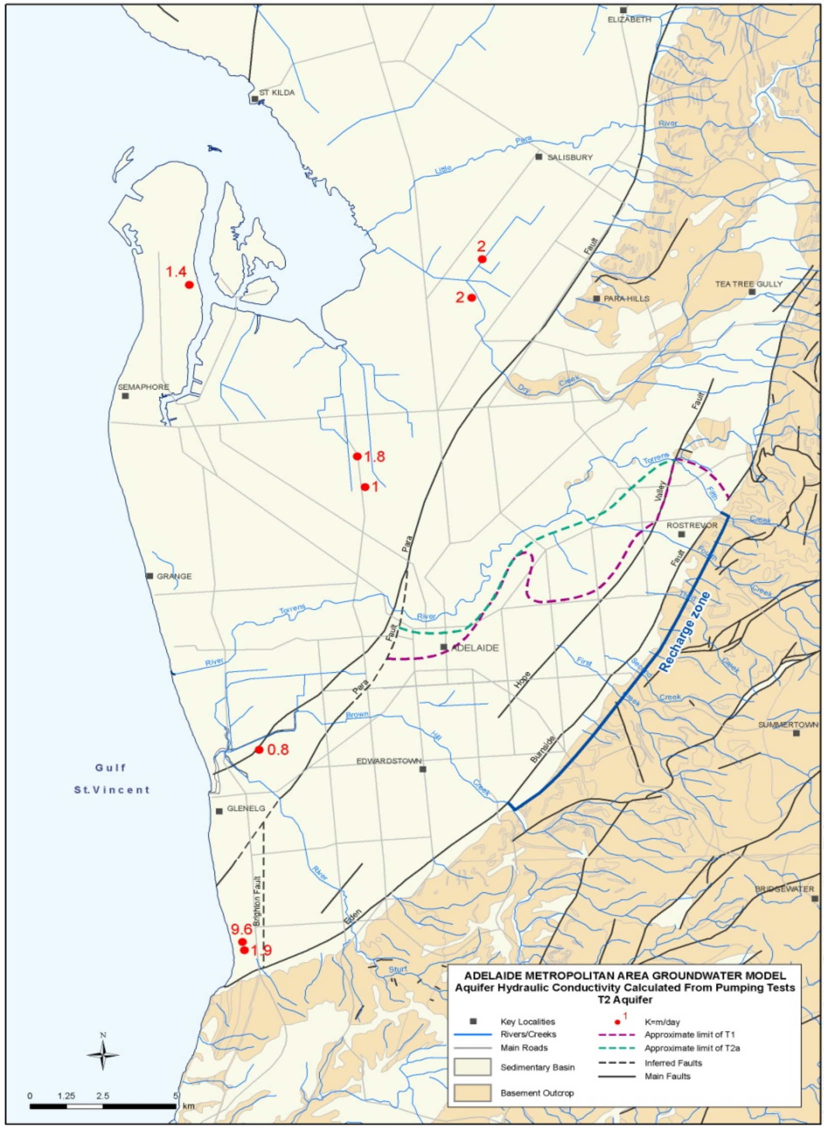


Figure 9. T2 aquifer hydraulic conductivity values

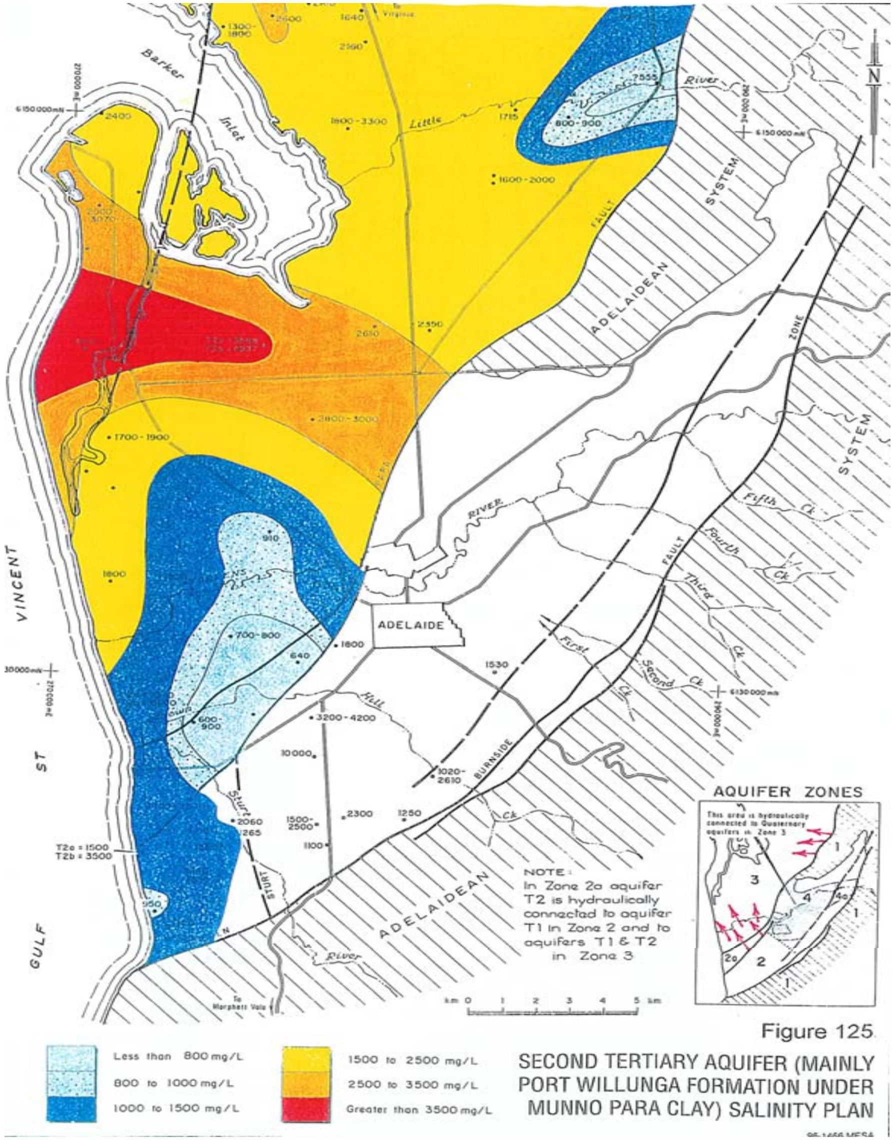


Figure 10. T2 aquifer pre-development salinity map

The low salinity zone below 1000 mg/L is restricted to western and southwestern suburbs at the Para Fault splinter block and Adelaide Plains Sub-basin.

The salinity distribution pattern is similar to the T1 aquifer.

This salinity distribution suggests that most of the recharge to the aquifer occurs as lateral flow.

Salinity stratification is evident within the T2 aquifer.

In the Little Para River area, low salinity groundwater (<1000 mg/L) occurs near the Para Fault as the result of lateral throughflow from the Fractured Rock Aquifer.

The two major low salinity corridors are separated by an area of relatively higher salinity, which is a similar pattern to the overlying T1 aquifer.

Table 9. Summary of T2 aquifer information

Zone	Equivalent stratigraphic units	Average thickness (m)	Main lithological description
4A	Absent		Absent
4	11[1]	15	Fine sand, silty and clayey.
2	11[1]	40	Fine sand, silty and clayey
	8 (west of Sturt River)	95	Limestone
2A	8	>70	Limestone
3	8	80–110	Limestone

1. revised, refer to Table 4

Table 10. Average values of T2 aquifer parameters

Zone	Transmissivity (m^2/d)	Storage coefficient	Thickness (m)	Hydraulic conductivity (m/d)	Remarks
2	200		100	1.9	Marion Golf Course
3	100	$2.84\text{x}10^{-5}$	100	1	Coopers Brewery
	188		105	1.8	Regency Park Golf Course

In **Zone 4**, this aquifer is now recognised as the T2a aquifer and generally has a salinity of less than 1500 mg/L. In Zone 2, the salinity data is limited to only one well which should not be taken as representative for the whole zone.

5.2.3 THIRD TERTIARY AQUIFER (T3)

This aquifer is defined as the third suite of saturated Tertiary sediments regardless of their stratigraphic age. In Zones 2 and 4, the T3 aquifer consists of the South Maslin Sand. It occurs at depths in excess of 190 m below ground and attains a maximum thickness of 25 m. The T3 aquifer contains brackish to saline groundwater with salinities ranging between 2400–16 000 mg/L.

In **Zone 2**, Gerges (1999) suggested the T3 aquifer east of the Sturt River is hydraulically connected to the T2 aquifer west of the river across the inferred Brighton Fault. This premise is based on limited stratigraphic information and if correct, would remove the discharge mechanism for the overlying T2 aquifer. As stated previously, it is now thought there is continuous flow within aquifers across the fault zone as shown in Figure 8. This cross section also shows that near the coast, the sandy beds of the Aldinga Member and Chinaman Gully

Formation are now considered to comprise the T3 aquifer (they were previously allocated to the overlying T2 aquifer).

The distribution of the T3 aquifer in **Zone 3** is not known with certainty, as it has only been intersected at Virginia in the Northern Adelaide Plains, and in the Allenby Gardens well, where 12 m of Chinaman Gully Formation sand was intersected 427 m below ground.

Within **Zone 4A**, there is effectively no T3 aquifer.

The T3 aquifer information is summarised in Table 11.

Table 11. Average values of T3 aquifer parameters

Well location and number	**Depth to top of aquifer** (m)	**Aquifer thickness** (m)	**Salinity** (mg/L)	**Water level** (m)	**Supply** (L/s)
Edwardstown 6628-12256	186	9	15 850	3	<1
Mitcham Railway Station 6628-13129	238	4–26	4 500	52	?
St James Reserve 6628-13116	226	5	8 410	–	–

5.2.4 FOURTH TERTIARY AQUIFER (T4)

In **Zone 2**, the T4 aquifer is limited to a narrow strip along the coast and west of the inferred Brighton Fault. It consists of the South Maslin Sand (previously called the T3 aquifer) and occurs at depths in excess of 400 m. It is an artesian aquifer with a head 21 m above ground level, with groundwater salinities in excess of 40 000 mg/L.

The T4 aquifer is well distributed over the **Zone 3** and extends northward into the Northern Adelaide Plains area. Generally it consists of up to 60 m of South Maslin Sand (and occasionally North Maslin Sand) and is separated from the overlying aquifers by the thick confining beds of the Blanche Point Formation. The T4 aquifer is very saline with values in excess of 80 000 mg/L.

Within **Zones 4 and 4A**, there is effectively no T4 aquifer. Aquifer information is summarised in Table 12.

Table 12. Average values of T4 aquifer parameters

Well location and number	**Depth to top of aquifer** (m)	**Aquifer thickness** (m)	**Salinity** (mg/L)	**Water level** (m)	**Supply** (L/s)
Allenby Gardens 6628-11477	532	39	120 000	25	0.7 tested
Grange 6628-8654	500	39	Not known	Not known	Not known
Dry Creek 6628-16687	~438	25–62	85 000	Flowing 6–18 m above ground	10
Minda Home 6627-6492	414	26	40 700	Flowing 21 m above ground	4
Pelican Point 6628-17874	?356	?9	~2 800	Flowing ?10 m above ground	1–2

5.3 FRACTURED ROCK AQUIFER

The Precambrian fractured rock aquifer (FRA), which forms the scarp face of the Adelaide Hills and underlies the St Vincent Basin, is believed to be primary source of recharge to the lower Quaternary aquifers and deeper Tertiary aquifers (Gerges, 1986).

The fractured rocks in **Zone 1** and adjacent to the Eden-Burnside Fault exhibit low salinities as a result of the active recharge occurring from high rainfall and surface water drainage. The salinity distribution indicates that low groundwater salinities below 1500 mg/L are associated with the highly fractured rock (quartzite, dolomite and sandstone) and major structures. Higher salinities over 1500 mg/L are associated with tillite and siltstone (Sturt Tillite). The most significant recharge area occurs between First and Fifth Creeks and is associated with Aldgate Sandstone, the Saddleworth Formation and Stonyfell Quartzite.

In **Zone 2**, two wells drilled in proximity to the Eden-Burnside Fault zone showed high salinities ranging between 13 000–22 000 mg/L. It is therefore anticipated that the remainder of this zone contains groundwater of high salinity. In the area west of the city, no information is available apart from the early documented records from the Croydon Well and the Mitchell Well, which both indicate salty water.

The flow direction in the FRA is towards the northwest, which is similar to the overlying Quaternary and Tertiary aquifer flow directions. This indicates the multi-aquifer groundwater system was in equilibrium prior to development. This also supports the revised recharge mechanism to all aquifers (Gerges, 1986), with lateral inflow from the fractured rock aquifer of the Mount Lofty Ranges being a significant component.

The baseflow from outcropping FRA sustains some of the flow in the River Torrens during dry periods.

FRA are generally not accessed in the **Zone 3** portion of the Adelaide Plains Sub-basin due to the large thickness of the overlying sediments.

In **Zone 4**, the lowest salinities are found along the River Torrens and in the vicinity of the Hope Valley Fault. The aquifers in this area are shallow and/or outcropping and were used extensively for irrigation during the 1950s and 1960s.

Within the Golden Grove Embayment (**Zone 4A**), the FRA underlying the undifferentiated Tertiary sediments exhibit lower salinity which increases towards the northwest, indicating groundwater flow towards Zones 2 and 4.

5.4 CONFINING BEDS

Similar to the aquifers in the Adelaide metropolitan area, the confining beds are also independent of conventional stratigraphic units and may be represented by different stratigraphic units in different areas (Gerges, 1999).

Gerges recognised 12 confining beds, with up to seven (Cb1 to Cb7) separating the Quaternary aquifers from each other and the underlying Tertiary aquifers. The Tertiary confining beds (Cb8 to Cb11) separate various Tertiary aquifers, while Cb12 is combination of a Tertiary confining bed (Unit 16) and the weathered bedrock clay (Unit 18). In most cases, Cb12 separates the deepest Tertiary aquifer from the underlying fractured rock aquifer.

The confining bed separating the T1 aquifer from the overlying Quaternary aquifers was identified as TQCb, and it may consist of any one of the confining beds from Cb2 to Cb7.

Ten wells were drilled in the Adelaide metropolitan and Northern Adelaide Plains areas to examine the hydraulic conductivity of some of confining beds separating the Quaternary and Tertiary aquifers. Results showed that vertical hydraulic conductivities for the Quaternary confining beds vary between 6.6×10^{-5} and 5.2×10^{-4} m/d.

A summary of the average measured vertical hydraulic conductivities for the Tertiary confining beds, including the TQCb confining bed, is presented in Table 13 (after Gerges, 1999).

Table 13. Average vertical hydraulic conductivities of Tertiary confining beds (m/d)

Aquifer	**Q's-T1**	**T1A-B**	**T1-T2**			**T2-T3**			**T3-T4**
Bed No	**TQCb**	**Cb8**	**Cb9**			**Cb10**			**Cb11**
Unit No		**U5**	**U7**	**U9**	**U10**	**U9**	**U10**	**U14**	**U14**
Zone									
2	$1.7x10^{-5}$	na	$2.1x10^{-6}$	$2.5x10^{-5}$	$6x10^{-7}$	–	–	$8.5x10^{-6}$	na
2A	$2.8x10^{-5}$	na	$2.1x10^{-6}$	–	–	$2.5x10^{-5}$	$6x10^{-7}$	–	$8.5x10^{-6}$
3A, B	$8.6x10^{-6}$	nm	$2.1x10^{-6}$	–	–	$2.5x10^{-5}$	$6x10^{-7}$	–	$8.5x10^{-6}$
3C,D,E	$1.6x10^{-5}$	nm	$2.1x10^{-6}$	–	–	$2.5x10^{-5}$	$6x10^{-7}$	–	$8.5x10^{-6}$
4	$1.6x10^{-5}$	na	–	–	$6x10^{-7}$	–	–	$4.8x10^{-4}$	na
4A	$1.1x10^{-5}$	na	na	na	na	na	na	na	na

na = not applicable nm = not measured

Horizontal hydraulic conductivities vary from 1.3 – 6.4×10^{-4} m/d and are presented by Gerges (1999) as an average value of 4.8×10^{-4} m/d. Cb10 in Zone 4 is highly permeable and horizontal conductivity of unit 14 is considered representative of both Kv and Kh.

Confining beds parameters derived from aquifer testing are presented in Table 14 (after Gerges, 1999).

Table 14. Confining bed vertical hydraulic conductivities from aquifer testing

Zone	**Aquifers separated**	**Thickness** (m)	K_v (m/d)	**Remarks**
2	Q'S – T1	15	3.5×10^{-5}	Bailey Reserve
	Q'S – T1	10	1.75×10^{-3}	Road Safety/Basketball Stadium
3C	T1A – T1B	40 (1)	9.3×10^{-5}	Kidman Park
	T1 – T2	10 (2)	5.8×10^{-6}	Kidman Park
3D	T1A – T1B	40 (1)	3.6×10^{-5}	Grange Golf Course
		10 (2)	9.0×10^{-6}	Grange Golf Course
3B	T1A – T1B	12	4.3×10^{-3}	Police Academy – Largs Bay

1. Thickness of 'Croydon facies' (Unit 5)
2. Thickness of Munno Para Clay (Unit 7)

5.5 SUMMARY OF REVISIONS TO GERGES (1999)

After re-evaluating newly available data from recent investigations, several revisions to the hydrogeological framework proposed by Gerges (1999) have been made.

The Carisbrooke Sand, which is present over large areas of the Adelaide Plains Sub-basin and the NAP, should be named the Carisbrooke Sand Aquifer rather than the Q4 and/or Q5 aquifer. It may be hydraulically connected to the underlying T1 aquifer in the Little Para River area only.

In **Zone 2A** (the Para Fault splinter block), Gerges (1999) originally suggested the T2 aquifer in this zone is hydraulically connected to the T1 aquifer in Zone 2, and to the T1 and T2 aquifers in Zone 3 due vertical displacement of the Tertiary sediments due to faulting – a view that was probably influenced by examining cross sections with a very large vertical exaggeration (20 x). In reality, the downwarping of the sediments across the fault zone occurs with a gradient of 1:13, which is relatively low. It is now thought that continuous flow within aquifers across the fault zone occurs – a view supported by recent drilling and aquifer testing.

In **Zone 4** (Golden Grove Embayment) where the Tertiary sediments lens out in the vicinity of the River Torrens, the hydrostratigraphic units should keep their assigned names from the deepest portion of the embayment where they were developed, with the following framework now adopted:

> The T1 aquifer in Zone 4 consists of the Carisbrooke Sand, Hallett Cove Sandstone/Dry Creek Sand and sand layers of the Ruwarung Member.
>
> The Aldinga Sand Member should be considered part of the T2a aquifer in Zone 4, as it is clearly a continuation of the T2a aquifer from Zone 2.
>
> The Chinaman Gully Formation (Tandanya Sand) aquifer should be considered as part of the T2b aquifer in the embayment. Over most of the embayment, this aquifer is separated from the overlying T2a aquifer by lignitic clay of Chinaman Gully Formation, and might be only locally connected to the overlying T2a aquifer.
>
> Accordingly, the South Maslin Sand would be the T3 aquifer in this zone as it is found in most of Zone 2 (to the east of the Brighton Fault).

Summary of aquifer distribution in each zone is presented in Table 15, where the Quaternary (Q1-Q6) and Tertiary (T1-T4) are designated in order of increasing depth, the fractured rock aquifer and confining beds are presented by the symbols P and C respectively.

Table 15. Summary of aquifer distribution (after Gerges, 1999) – revised

Hydro-geological units	Zones and associated aquifers									
	1	2	2A	3A	3B	3C	3D	3E	4	4A
1	X	Q1-Q4	Q1-Q4	Q1-Q5	Q1-Q5	Q1-Q6	Q1-Q6	Q1-Q6	Q1-Q?	Q1-Q5
2	X	X	X	NK	NK	C	C	C	X	X
3	X	? Qpac[1]	T1a	Qpac[1]	Qpac[1]	X	X	X	Qpac/T1[1]	T1
4	X	T1a	T1a	T1a	T1a	T1a	T1a	T1a	X	X
5	X	C(1)	C(1)	C(1)	C(1)	C	C(1)	C(1)	X	X
6	X	T1b(1)	T1b	T1b	T1b	T1b	T1b	T1b	X	X
7	X	C(2)	C(2)	C(2)	C(2)	C(2)	C(2)	C(2)	X	X
8	X	T1	T2	T2	T2	T2	T2	T2	X	X
9	X	T1-C	C	C	C	C	C	C	T1	X
10	X	C	C	C	C	C	C	C	C	X
11	X	T2a-T3a	T3a	T3a	T3a	T3a	T3a	T3a	T2a[2]	T1
12	X	C[3]	C	C	C	C	C	C	C	T1
13	X	T2b/T3b[4]	T3b	T3b	T3b	T3b	T3b	T3b	T2b[4]	T1
14	X	C	C	C	C	C	C	C	C	T1
15	X	T3-T4	T4	T4	T4	T4	T4	T4	T3[5]	T1
16	X	C	C	C	C	C	C	C	C	T1
17	X	NK	NK	NK	NK	T4	NK	NK	T1	T1
18	C	C	C	C	C	C	C	C	C	C
19	P	P	P	P	P	P	P	P	P	P

[1] revised, was Q4/Q5

[2] revised, was T1

[3] revised, was T2

[4] revised, were T1-T2 (zone 4) and T1-T2 (zone 2)

[5] revised, was T1-T3

Other symbols used in Table 4 are presented below:

T1a - first Tertiary aquifer, subaquifer a

T1b - first Tertiary aquifer subaquifer b

T1b(1) - upper Port Willunga Formation, present near the coast only

C(1) - ‘Croydon facies’: partly acts as a semi-confining bed

C(2) - Munno Para Clay Member: confining beds interbedded with thin layers of limestone

X - not significantly present

NK - not known

Table 16. Stratigraphy and Hydrostratigraphy of the Adelaide Plains Sub-basin and Golden Grove Embayment (revised from Hodgkin)

Age		Golden Grove Embayment			Adelaide Plains Sub-Basin		
		Stratigraphy	Hydrostratigraphy	Description	Stratigraphy	Hydrostratigraphy	Description
Quaternary	Holocene	Semaphore Sand, modern alluvium and beach gravels	Unconfined Aquifer	Thin sand aquifers restricted mainly to coastal areas	Semaphore Sand, modern alluvium and beach gravels	Unconfined Aquifer	Thin sand aquifers near coast
					Saint Kilda Formation	Unconfined Aquifer	Thin sand, shell aquifers near coast
	Pleistocene	Pooraka Fmn	Aquitard		Pooraka Fmn	Aquitard	
		Keswick Clay	Aquitard		Keswick Clay	Aquitard	
		Hindmarsh Clay	Aquitard, Q1–Q5 Aquifers	Mainly clay aquitard with interbedded sandy aquifers	Hindmarsh Clay	Aquitard, Q1–Q6 Aquifers	Mainly clay aquitard with interbedded sandy aquifers
	Pliocene?	Carisbrooke Sand	T1 Aquifer Carisbrooke Sand Aquifer	Thin sandy mainly confined aquifer with restricted extent	Carisbrooke Sand	Carisbrooke Sand Aquifer	Confined sandy aquifer, most significant in eastern side of NAP PWA
Tertiary	Pliocene	Hallett Cove Sandstone and Dry Creek Sand	T1a Aquifer	Thin sandy confined aquifer restricted to western areas	Dry Creek Sand	T1 Aquifer T1a Aquifer	Confined sandy aquifer, thickening to the south-west
		Croydon Facies		Semi-confining bed	Croydon Facies		Semi-confining bed
	Miocene to Oligocene	Port Willunga Formation Upper Limestone	T1b Aquifer	Confined aquifer, mainly limited to area between Para Fault splinters	Port Willunga Formation Upper Limestone	T1b Aquifer	Confined aquifer, thickening to south and south-west
		Munno Para Clay Member	Aquitard	Confining bed limited to western areas	Munno Para Clay Member	Aquitard	Confining bed, absent in north of NAB PWA
		Lower Limestone Undifferentiated Sand	T1 or T2 Aquifer	Confined aquifer, extent limited to south-west areas	Lower Limestone	T2 Aquifer	Thick confined aquifer, sandy and thinning in north and north-east of NAB PWA
		Ruwarung Member	Aquitard T1 Aquifer	Mainly confining bed Restricted extent	Ruwarung Member	Aquitard	
		Aldinga Member	Aquitard T2a or T3 Aquifer	Clay unit Variable sand	Aldinga Member	Aquitard T3 Aquifer	Clay unit Sand unit
	Eocene	Chinaman Gully Formation	Aquitard T2b or T3 Aquifer	Clay unit Variable sand	Chinaman Gully Formation	Aquitard and T3 Aquifer	Mainly confining bed, minor thin sandy aquifer
		Blanche Point Fmn	Aquitard	Confining bed	Blanche Point Fmn	Aquitard	Confining bed
		Tortachilla Limestone	T3–T4 Aquifer	Thin confined aquifer	Tortachilla Limestone	T4 Aquifer	Thin confined aquifer
		South Maslin Sand		Thin confined aquifer, thickest in the east	South Maslin Sand		
		Clinton Formation	Aquitard	Confining bed, restricted extent	Clinton Formation	Aquitard	Confining bed, restricted extent
		North Maslin Sands	T3–T4 Aquifer	Thin confined sandy aquifer	North Maslin Sands	T4 Aquifer	Confined sandy aquifer

6. PRE-DEVELOPMENT CONDITIONS

6.1 QUATERNARY AQUIFERS

Recharge from surface drainage and leakage from overlying and/or underlying aquifers has been considered to be major component of inflow to the shallow Quaternary aquifers (Q1-Q3). In the deeper aquifers (Q4-Q6), historic water levels suggest that most recharge occurred as lateral throughflow, combined with minor downward or major upward leakage.

6.2 TERTIARY AQUIFERS

Miles (1952) originally suggested that recharge to the Tertiary aquifer system occurred from downward infiltration from surface drainage. Shepherd (1978) also concluded that the salinity of both Tertiary aquifers had been strongly influenced by infiltration from the Torrens, Little Para and Gawler Rivers.

Gerges (1999) deduced the major recharge to the Tertiary system occurs from the basement rocks of the Mt Lofty Ranges along the Eden-Burnside Fault in Zone 4A, and also along the Para Fault near the Little Para River in Zone 3A. Also, low salinity groundwater was intersected at 285 m in the fractured rocks underlying the sediments, suggesting direct recharge from the adjacent hills aquifer through the fault zone. The salinity gradually increases towards the northwest indicating groundwater flow in that direction.

The historic artesian conditions of the T1 and T2 aquifers in Zone 3 imply upward leakage into the overlying aquifers.

The discharge mechanism at the western extremity of the study area is not well known, but structural evidence suggests presence of major faults under St Vincent Gulf, which may possess sufficient permeability to allow restricted discharge from the T1 aquifer.

The predevelopment inflow mechanisms into various aquifers and in various zones are shown in Table 17.

Stable isotope and radiocarbon groundwater data for the T1 aquifer in the Adelaide Metropolitan Area were collected between 1986 and 1992. The major findings are:

- Groundwater in Zone 4A is relatively young, indicating recharge occurring in this area, possibly along the fault system.
- Flow velocities vary between 0.3 and 2.9 m/y.
- The highest flow velocities occur as groundwater crosses the Para Fault indicating preferred recharge in the vicinity of the fault.
- Lower flow velocities occur downgradient and reflect the low hydraulic gradient between the Para Fault and the Gulf (Deighton et al, 1994).

Gerges (1999) found all aquifers exhibit a general flow towards the northwest or west, with discharge into and beneath the Gulf, and into the Torrens River as shown in Figure 11.

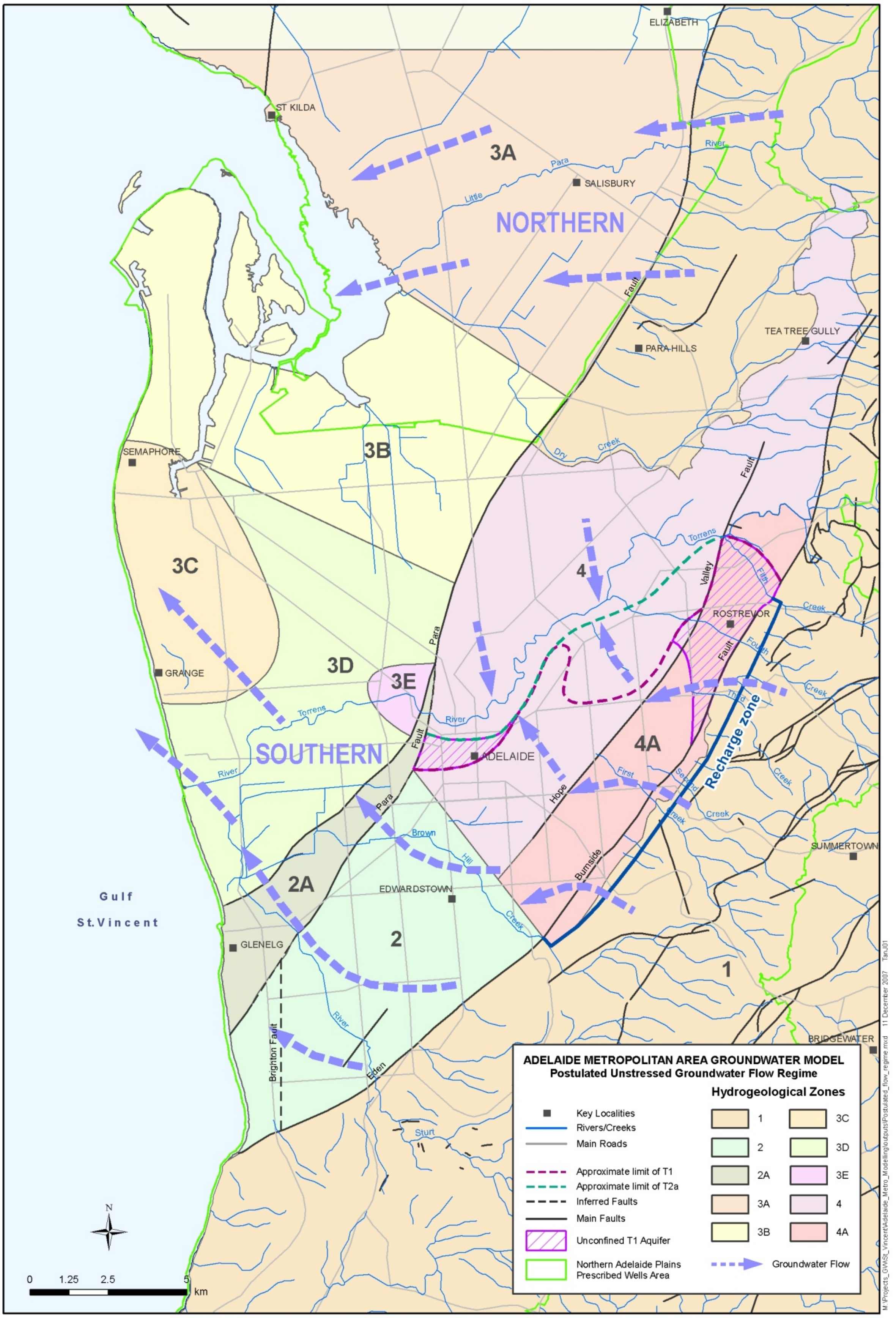


Figure 11. Postulated unstressed groundwater flow regime (Gerges 1999)

Table 17. Predevelopment flow mechanisms, revised from Gerges (1999)

Zone	Q1 to Q3 aquifers	Q4 To Q6 aquifers	T1 aquifer	T2 aquifer	T3/T4 aquifer	P aquifer
4a	Surface drainage (Q1) Downward leakage (Q2 and Q3) Lateral flow from zone 1	Lateral flow from zone 1 Downward leakage almost equal to lateral flow No Q6 aquifer	Mainly lateral flow from zone 1 Minor downward leakage from Q5	Not applicable Included in T1 aquifer	Not applicable Included in T1 aquifer	Lateral flow from zone 1
4	Surface drainage (Q1) Downward leakage (Q2 and Q3) Lateral flow from zone 4a	Lateral flow from zone 4a Downward leakage almost equal to lateral flow No Q5 and Q6 aquifers	Lateral flow from T1 and Q5 aquifers in zone 4a Minor lateral flow from laterally interconnected Q2, Q3 and Q4 aquifers in zone 4a Downward leakage from Q4 aquifer	Lateral flow from T1 aquifer in Zone 4 a Downward leakage from T1 in zone 4	Lateral flow from T1 aquifer in zone 4a[1]	Lateral flow from P aquifer in zone 4a Possible lateral flow and/or downward leakage from sedimentary aquifers in zone 4
2	Surface drainage (Q1) Downward leakage (Q2 and Q3) Lateral flow from zone 1	Lateral flow from zone 1 Downward leakage is almost double of lateral flow No Q6 aquifer	Lateral flow from T1 aquifer in zone 4a Possible preferential lateral flow from zone 1, quartz and dolomite veins Minor lateral flow from laterally interconnected Q3, Q4 and Q5 aquifers Minor downward leakage	Lateral flow from T1 aquifer in zone 4a Minor unknown upward leakage from T3 aquifer	Not known (possible lateral flow from T1 aquifer in zone 4a) Possible minor upward leakage from P aquifer	Lateral flow from zone 1
2a	Upward leakage from underlying aquifers Lateral flow from zone 2	Upward leakage from underlying T1 aquifer Lateral flow from T1 aquifer in zone 2 No ?Q5 and Q6 aquifers	Lateral flow from T1 aquifer in zone 2 Upward leakage from T2 aquifer	Lateral flow from T1 aquifer in zone 2 Upward leakage not known? Minor upward leakage from T3	Possible lateral flow from T2/T3 aquifers in zone 2 Upward leakage is unknown	Not known (possible lateral flow from zone 2)
3C, 3D, 3E	Surface drainage (portion of Q1) Upward leakage from underlying aquifers Lateral flow from zone 2a	Q4, lateral flow from Q4 in zone 2a and upward leakage from Q5 Q5 and Q6, lateral flow from T1 aquifer in zone 2a and upward leakage Q6 upward leakage occurs from T1 aquifer	Lateral flow from T1 aquifer in zone 2a Upward leakage from T2 aquifer	Lateral flow from T2 aquifer in zone 2a Minor upward leakage from T3 aquifer	Possible lateral flow from T3 and P aquifers in zone 2a Upward leakage is unknown	Not known (possible lateral flow from zone 2a)

6.3 PRE-DEVELOPMENT WATER BUDGET

Prior to groundwater development, the historic flow regime was in equilibrium where the total inflow was equal to the total outflow, with no change in storage in accordance to the law of conservation of matter.

The Fractured Rock Aquifer (FRA) in Zone 1 and adjacent to the Eden-Burnside Fault, is recharged directly from rainfall and surface water infiltration. The FRA is the source of the recharge to the sedimentary aquifers in Zones 2, 3A and 4A, with the total potential recharge volume calculated to be 12 000 ML/y, based on the calculated lateral flow through the aquifers (Gerges, 1999). The exception is the Q1 aquifer where lateral throughflow is equal to outflow from the FRA and recharge from surface drainage. Table 18 indicates a surplus of about 3950 ML/y that represents a potential additional resource from the FRA in the area.

Table 18. Summary of total outflow from the Fractured Rock Aquifer

Recharge area	**Available recharge** (ML/y)	**Total inflow to all aquifers** (ML/y)	**Surplus of recharge** (ML/y)
First Creek to Fifth Creek	8 600	6 850	1 750
Brown Hill Creek to First Creek	3 400	1 200	2 200
Total (Brown Hill Creek – Fifth Creek)	**12 000**	**8 050**	**3 950**

Most of the inflow into the Quaternary aquifers occurs from leakage between aquifers and lateral flow from other aquifers. In some cases, this leakage is estimated to be twice the amount of lateral inflow.

The majority of flow into the Tertiary aquifers originates from lateral inflow from the FRA in the Adelaide Hills. The Tertiary aquifer in Zone 4A acts as a significant conduit of about 4400 ML/y from the FRA to other Tertiary aquifers in the study area. Downward leakage from the Quaternary aquifers into the Tertiary aquifers occurs in Zones 2, 4 and 4A, but is insufficient to cause a major salinity impact.

Table 19 summarises the inflows from the FRA and surface drainage, and also the outflows from all aquifers in the area south of the River Torrens. This is called the southern flowpath, and is delineated in Figure 11.

Table 19. Summary of total inflow and outflow – southern flowpath (ML/y)

INFLOW		**OUTFLOW**	
All Quaternary aquifers	1 900	Into Torrens River	3 800
All Tertiary aquifers	4 400	Into Gulf St Vincent	4 350
Fractured rock aquifer	2 300	Evapotranspiration and baseflow	450
ALL AQUIFERS	**8 600**	**ALL AQUIFERS**	**8 600**

Total Inflow (**8600 ML**) – Total Outflow (**8600 ML**) = Change in Storage (**0 ML**)

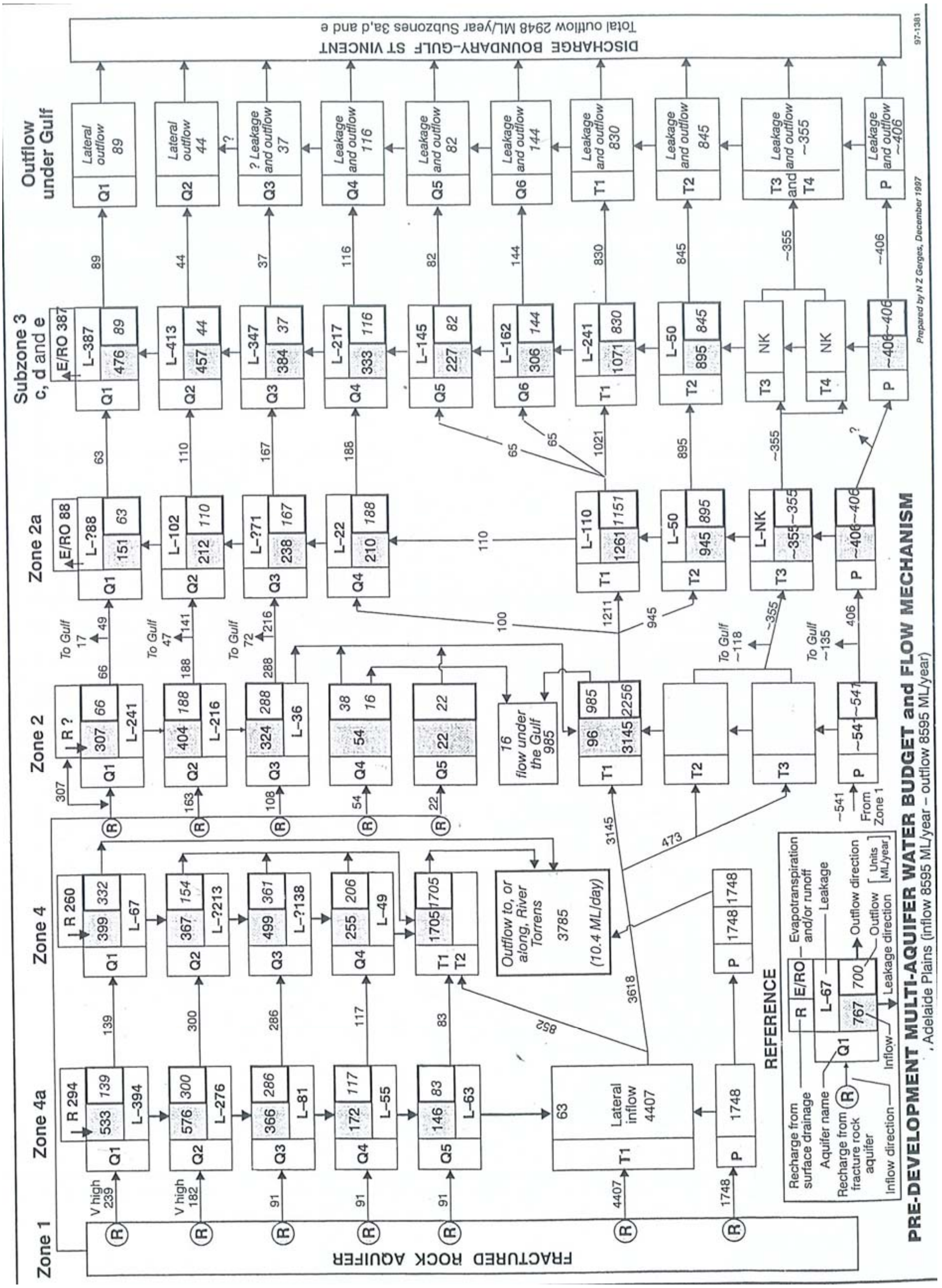


Figure 12. Pre-development water budget and flow mechanism (Gerges, 1999)

The water balance for the northern flowpath in Zone 3A, which follows the Little Para River and extends to the Gulf in Zone 3B, is summarised in Table 20.

Table 20. Summary of total inflow and outflow for the northern flowpath (ML/y)

INFLOW		OUTFLOW	
Q1, Q2 and Q3 aquifers	1 300	Into Gulf St Vincent	3 000
Q4 aquifer	350		
T1 and T2 aquifers	1 350		
ALL AQUIFERS	**3 000**	**ALL AQUIFERS**	**3 000**

Total Inflow (**3000 ML**) – Total Outflow (**3000 ML**) = Change in Storage (**0 ML**)

Figure 12 illustrates the predevelopment multi-aquifer water budget and flow mechanisms for both the above flowpaths including recharge from the fractured rock aquifer, inflow into sedimentary aquifers and outflows.

The total water budget of the whole study area is the sum of water balances for both northern and southern flowpaths:

Inflow – Outflow = Change in storage

(8600 + 3000 ML) – (8600 + 3000 ML)

11 600 ML/y – 11 600 ML/y = 0

7. CURRENT STATUS

7.1 GROUNDWATER EXTRACTION

Until recently, the groundwater resources of the Golden Grove Embayment and most of the urban area within the Adelaide Plains Sub-basin were not prescribed and consequently, accurate data of groundwater extraction was not collected on a regular basis.

Historically, the largest groundwater users have been industrial users, SA Water (formerly E&WS Department), local government and schools, and golf clubs. Between 1914 and 1968, the E&WS Department intermittently supplemented the mains water supply during periods of drought with the pumping from the T1 aquifer. Miles (1952) and Gerges (1999) detail quantities and timing of this groundwater use, and estimate the locations of the pumping centres.

The earliest estimates of irrigation and industrial extractions from the Tertiary aquifers of between 4500–5500 ML/y were given by Miles (1952) and were derived from a water use survey. From 1981 to 1984, a groundwater usage survey was conducted and reported by Edwards et al (1987), and data is presented in Figure 14. Gerges (1999) compiled an estimate of annual groundwater discharge from the T1 aquifer based on the above sources (Fig. 13).

Current groundwater extraction from the T1 aquifer is in the range of 7500–8000 ML/y, comprising the estimates by Edwards et al (1987), additional extraction of ~750 ML/y in the Thebarton area since the late 1980s, extraction by several western suburb golf clubs (1250–1500 ML/y) and increased industrial pumping by Penrice Soda Products at Osborne. The current distribution of production wells is very similar to that shown in Figure 14.

Current T2 aquifer extraction in the Metropolitan Area is considered to be very limited. In the Regency Park area, Coopers Brewery extracts 300–400 ML/y, with a lesser amount approximating 200 ML/y being pumped by the Regency Park Golf Course.

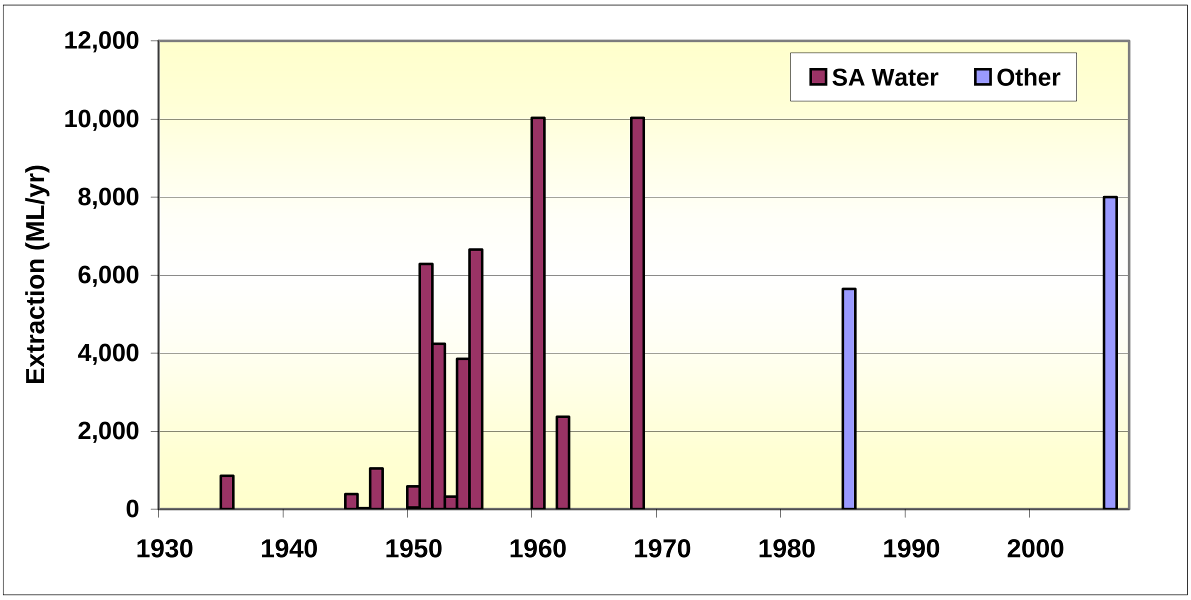


Figure 13. Estimates of groundwater abstractions (after Gerges, 1999)

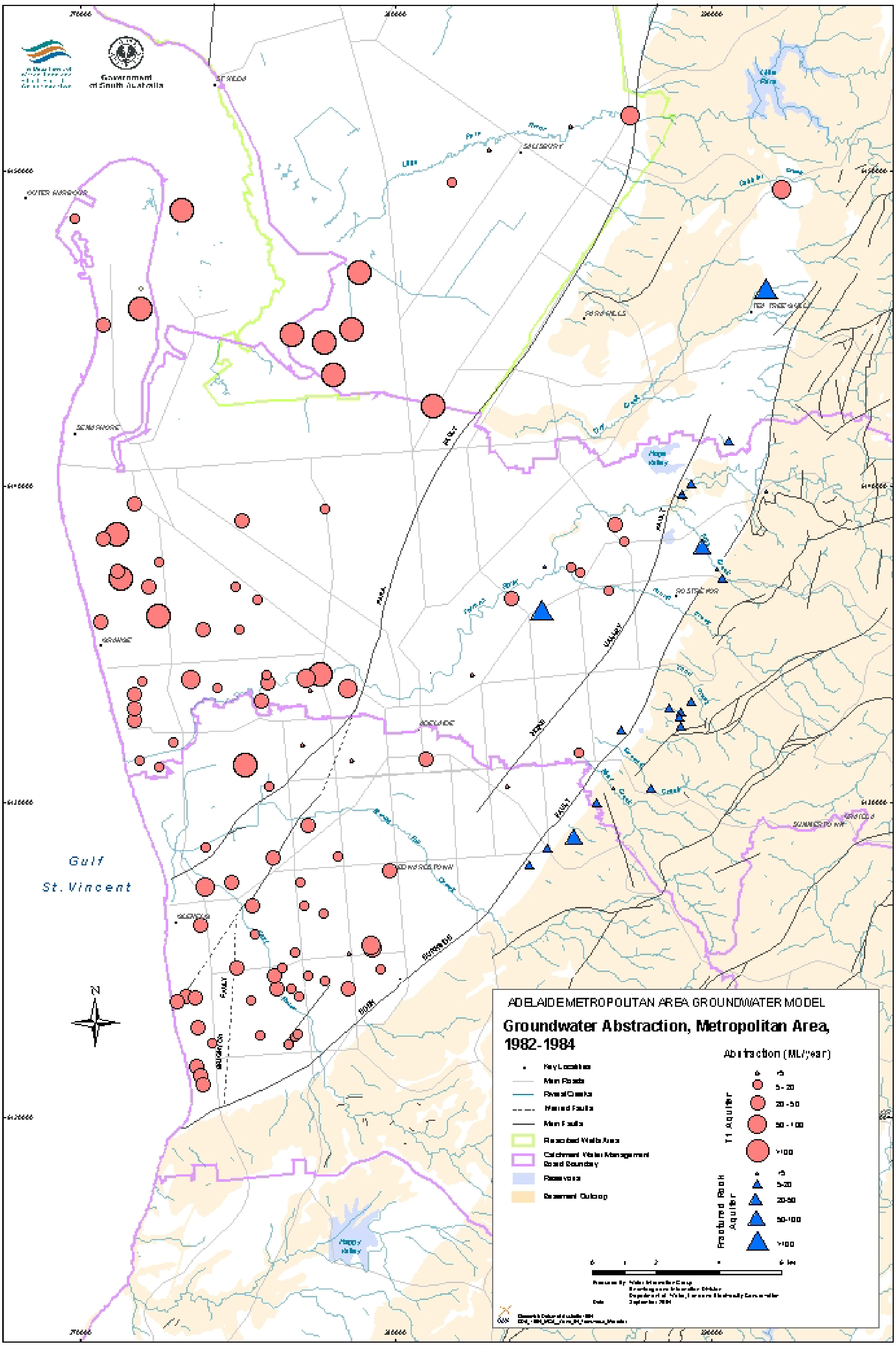


Figure 14. Groundwater abstractions from 1983 survey (after Hodgkin, 2004)

7.2 POTENTIOMETRIC SURFACES

7.2.1 T1 AQUIFER

In response to the extractions outlined above, the T1 aquifer currently exhibits cones of drawdown coinciding with known pumping centres:

Little Para River (irrigation)

Penrice and SAMCOR (industrial)

West Lakes (irrigation)

Torrens Valley (irrigation)

Thebarton (industrial).

The analysis of the potentiometric surface development (Gerges, 1999) is summarised below, with comparisons between 1997 and 2007 presented in Figures 15 and 16.

Winter potentiometric surface (based on September readings – Fig. 15):

Permanent head loss from the aquifer has occurred since at least 1936.

The 1951 potentiometric surface map shows the first indications of incomplete recovery, with permanent cones of depression developing during the mid 1950s.

The major cone of depression occurs in Zone 3 north of the Torrens River. During drought and heavy E&WS pumping, the cone of depression spreads south of the river into Zone 2.

The location of the recent permanent cone of depression in Zone 3 corresponds to the location of pumping centres at Penrice, Thebarton and western golf courses.

During the late 1990s, the cone of depression decreased to its minimum size at the end of winter (Fig. 7), but the potentiometric surface never recovered fully due to:

- continuous industrial pumping during winter
- the duration of the recovery period is short in comparison to the pumping period
- the effect of cumulative residual drawdown over years of pumping, particularly during summer has led to a significant loss from elastic storage, which shows a continuous decline in water level.

The current winter potentiometric surface generated for September 2006 shows a similar location and extent of the cones of depression to that measured in 1997, with a slight further expansion of the cone in the West Lakes – Grange area to the south.

Summer potentiometric surface (based on March readings – Fig. 16):

The present potentiometric surface displays steep cones of depression at their maximum level.

Extensive and continuous pumping from Zone 3 has generated a regional cone of depression in the aquifer, which has formed major new flow directions:

- toward the Penrice - SAMCOR pumping centre from the east, west and northwest
- toward the West Lakes pumping centre from the north and west.

Again, the current potentiometric surface map generated for March 2007 is similar to that for 1997, with a slight further expansion of the cone in the West Lakes – Grange area in all directions (Fig. 16).

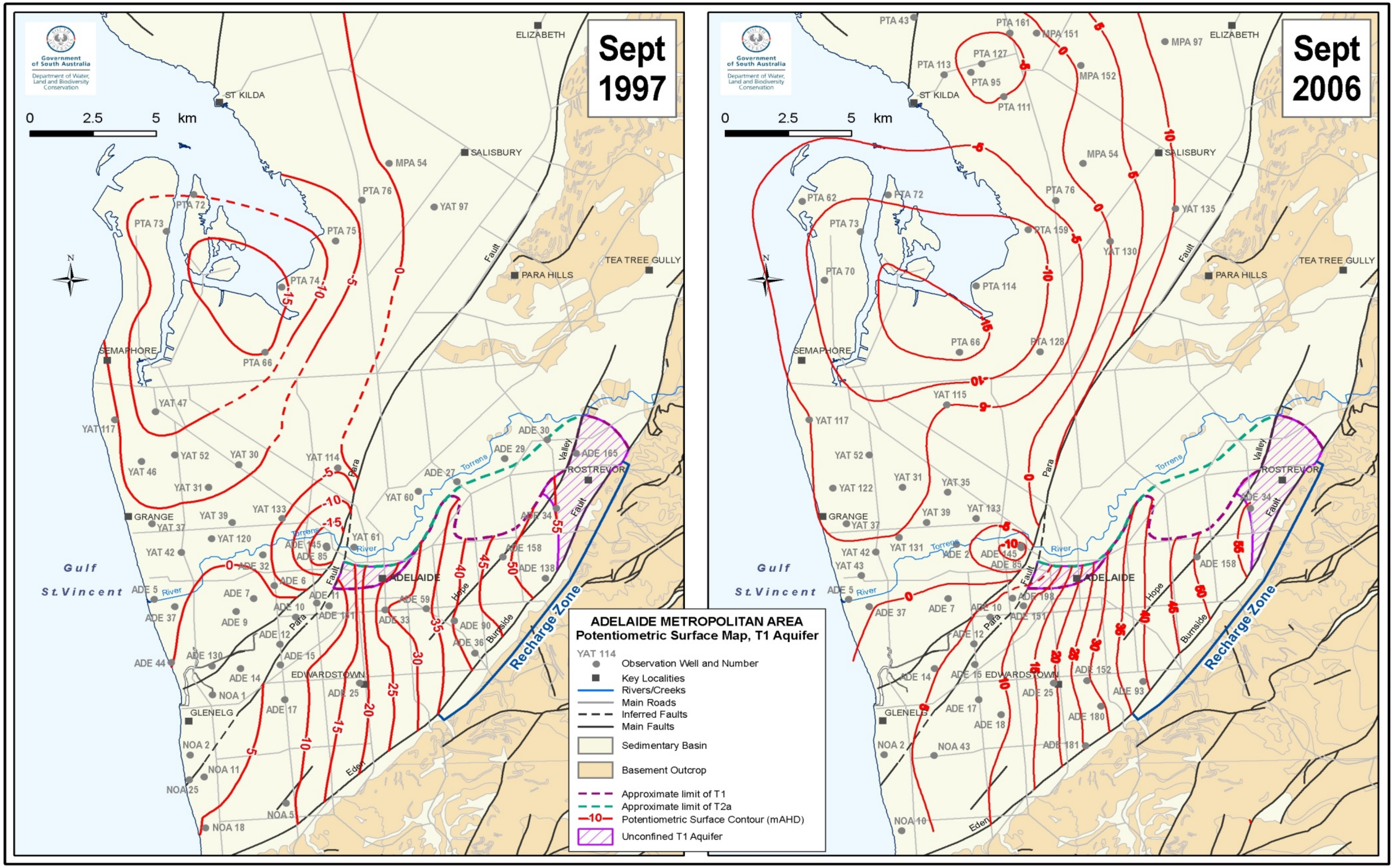


Figure 15. T1 aquifer potentiometric surface map – September. Comparison between 1997 and 2006

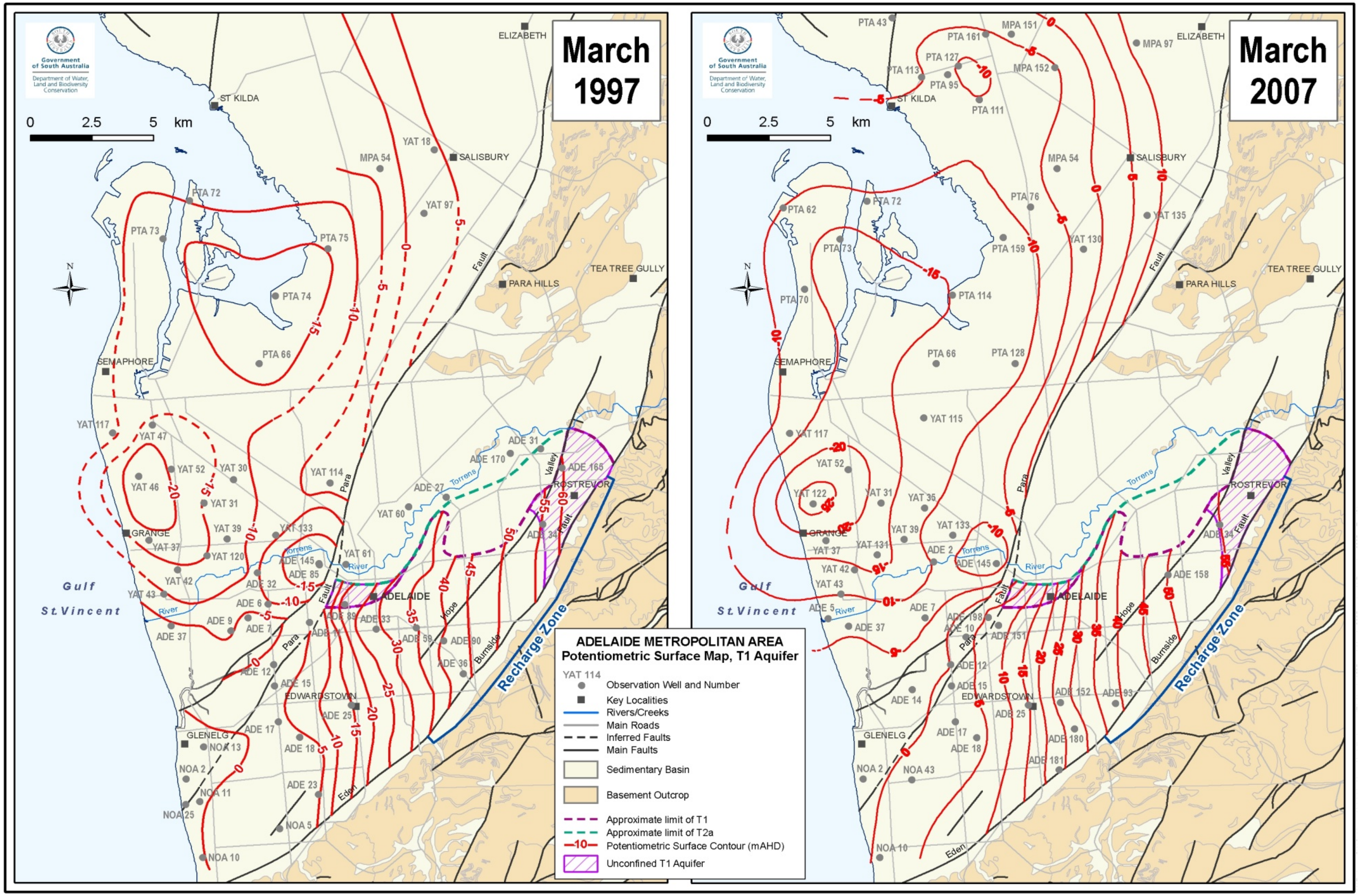


Figure 16. T1 aquifer potentiometric surface map – March. Comparison between 1997 and 2007

7.2.2 T2 AQUIFER

Until recently, there has not been significant pumping from the T2 aquifer in the Adelaide Metropolitan Area, as there are were only seven wells extracting water:

Two for irrigation of golf courses at Regency Park and Riverside.

Five for industrial use by Penrice Soda in the Osborne area, Tip–Top Dry Cleaning and three for Coopers Brewery.

The change in water levels over the past 45 years is due to the permanent loss of head, which varies from 4 m near the coast, to 12 m in the Little Para River area.

The permanent head loss is the result of:

upward leakage to the heavily pumped T1 aquifer in the western suburbs

reduction in lateral flow from the Tertiary aquifers in the Para Fault splinter block

heavy extraction in the Northern Adelaide Plains PWA.

Since September 2006, a permanent cone of depression has developed in the Osborne area where the pressure level has dropped by approximately 20 m as a result of the extraction of 1200 ML/y from the T2 aquifer for industrial use by Penrice Soda (Fig 17).

Extensive and continuous pumping from two major pumping areas, Penrice Soda at Osborne and Coopers Brewery, has generated a permanent regional cone of depression in the aquifer, which has formed major new flow directions:

Towards the Osborne pumping centre from the north, west and south,

Towards the Coopers Brewery pumping centre from the north and west.

The current potentiometric surface map generated for March 2007 is similar to that for September 2006, however the cone of depression has expanded further in all directions (Fig 17).

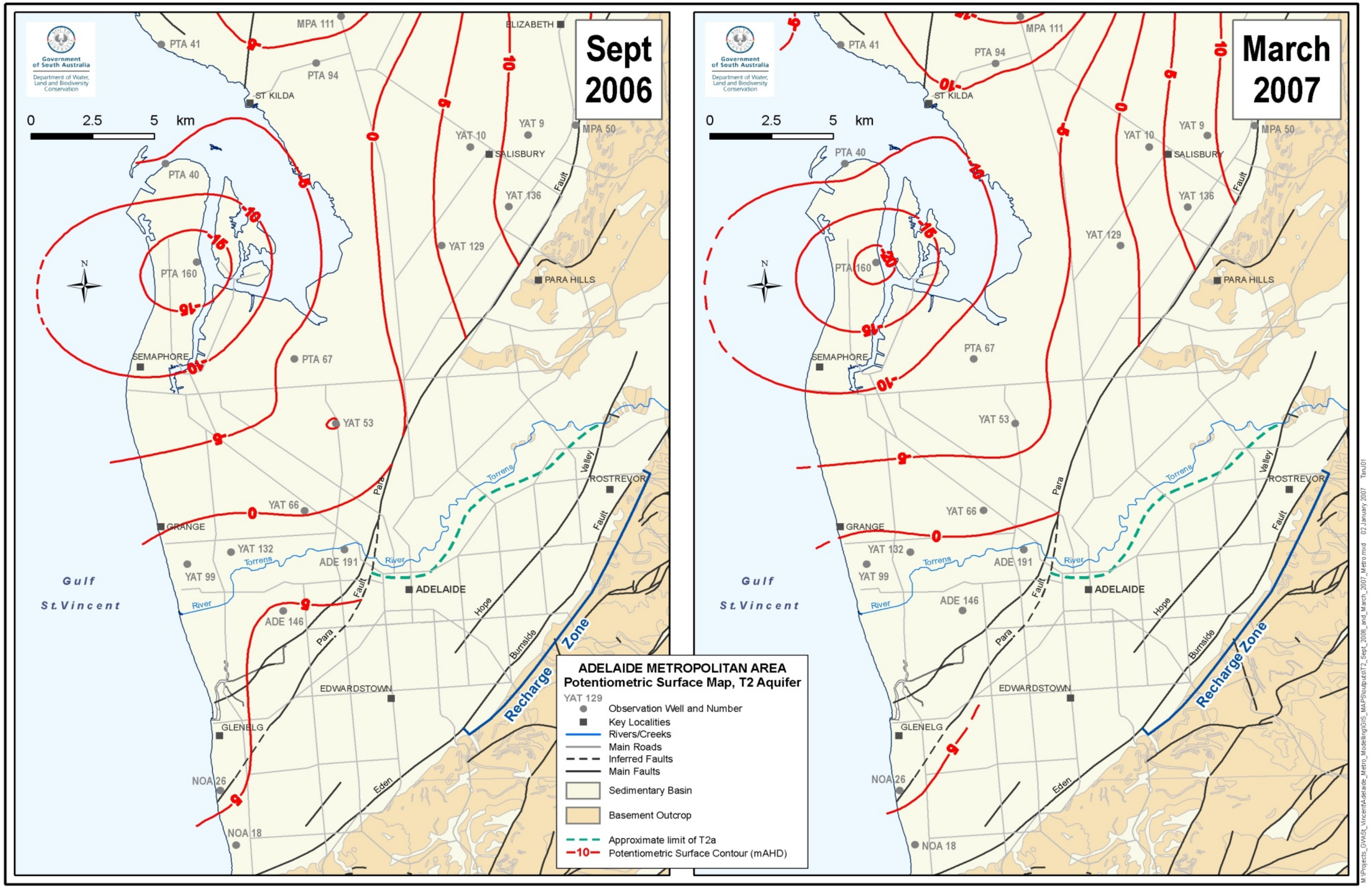


Figure 17. T2 aquifer potentiometric surface maps for September 2006 and March 2007

7.3 GROUNDWATER LEVEL TRENDS

7.3.1 T1 AQUIFER

The groundwater level fluctuations in the T1 aquifer can be divided into four groups :

- Major seasonal fluctuations caused by summer irrigation pumping, with declines in groundwater level during summer and recovery in winter. The West Lakes area in Zone 3 experiences seasonal changes of 20 m, and Zone 2 up to 4 m. Zones 4 and 4A has only small groundwater level changes, suggesting little or no pumping.
- Permanently stressed areas where industrial pumping occurs all year round, such as Penrice - SAMCOR and Thebarton, where recorded fluctuations are much smaller (only up to 4 m) than those due to summer irrigation.
- Minor fluctuations caused by tidal effects or barometric changes (-0.01 to 0.4 m).

The long-term decline in water levels over the whole area is due to increased extraction and the effect of cumulative residual drawdown (incomplete recovery). The trends of winter peaks are different to those of summer lows.

The winter peaks can be grouped into four stages: 1900–50, 1951–60, 1960–84 and 1984–98. During the first stage a sharp decline was the response to initial heavy pumping, the second and third stage represent a constant pumping averaging ~5000 ML/y and the fourth stage indicates an increase in the total extracted.

The summer lows have three trends:

- Same trends as winter peaks indicating constant pumping from these areas over each stage.
- Continuous but steady decline in summer level (with reasonably constant winter level), indicating increases in summer pumping.
- No evident pattern.

Between 1998 and 2007 (stage 5), 12 out of 45 observed wells generally show a decline in pressure levels, suggesting an overall increase in the total extraction compared to the 1998 levels. One well (PTA 73) shows no increase or decrease in pressure level. A slight decrease in pressure level was recorded in the Thebarton area, whilst two wells in the West Lakes area (YAT 52, 122) show considerable declining trends which are most likely the result of an increase in extraction.

Comparison of hydrographs from the West Lakes - Grange pumping area (YAT 31, 37 and 42 – stable trend; and YAT 52, 117 & 122 – declining trend) seems to indicate that pumping centres have been shifting towards the northwest since 1998.

Locations of current water level monitoring wells are presented in Figure 18, together with representative hydrographs for each zone.

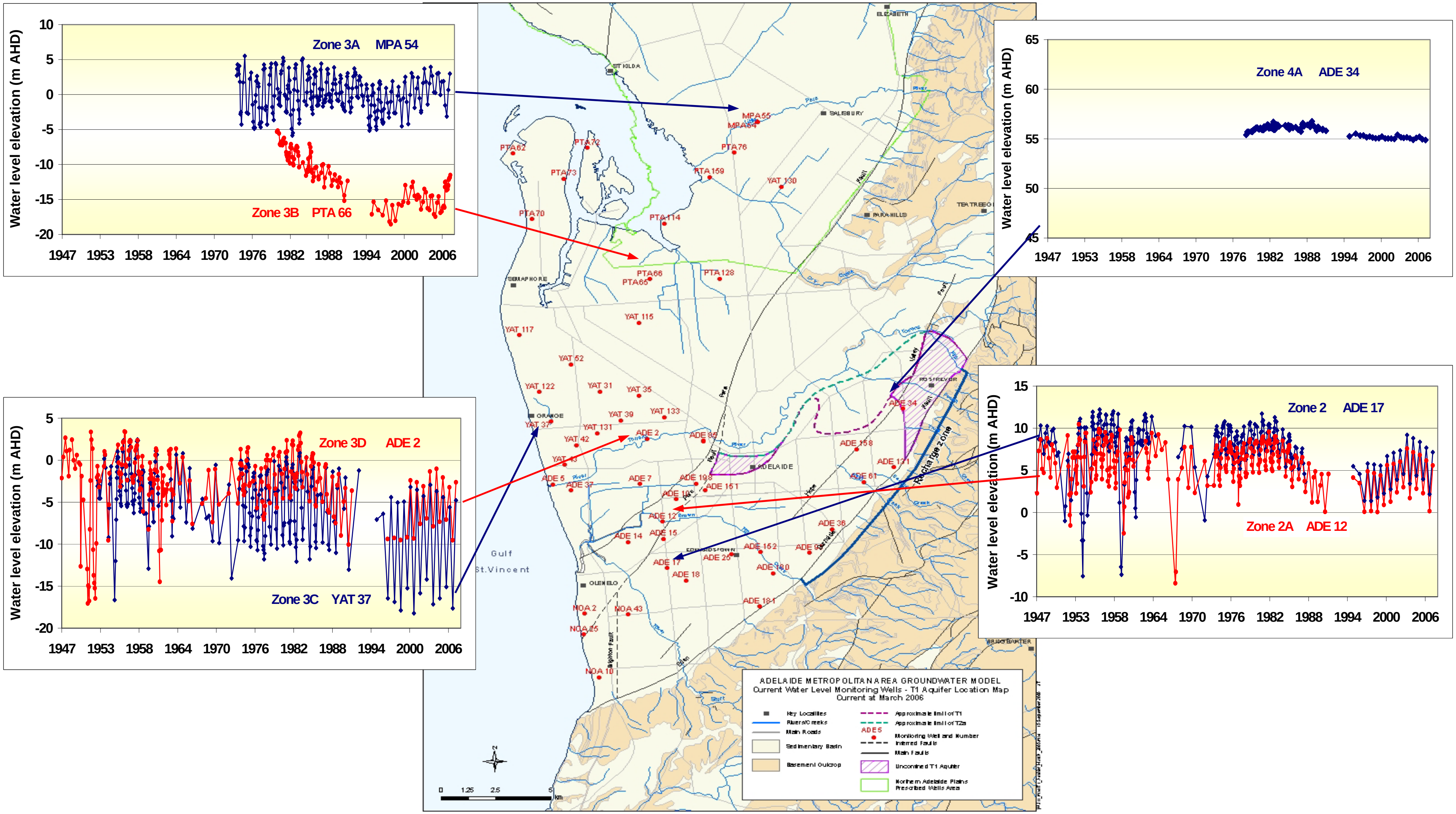


Figure 18. Current T1 aquifer monitoring wells and representative hydrographs

7.3.2 T2 AQUIFER

Long-term records show seasonal fluctuations as well as an overall rate of decline of 0.35 to 0.5 m/y. Recent monitoring (1999–2007) shows seasonal fluctuations and an overall decline of the pressure level. The largest declines were recorded in YAT 53 at Regency Park golf course, and PTA 40 and 67 with falls of 0.64, 0.27 and 0.09 m/y respectively. The decline is most likely due to extraction at the Coopers Brewery (gradual decline commencing in 2001), and Penrice Soda at Osborne (steeper trend commencing in 2006).

The locations of current T2 aquifer monitoring wells are presented in Figure 19, together with representative hydrographs.

7.3.3 FRACTURED ROCK AQUIFER

Current FRA water level monitoring wells are presented in Figure 20. Selected hydrographs show a seasonal fluctuation in response to summer pumping and the effects of winter recharge. Some of the observed water level decline is due to pumping for the irrigation of vegetables, which has resulted in a depletion of storage from poorly interconnected fracture zones.

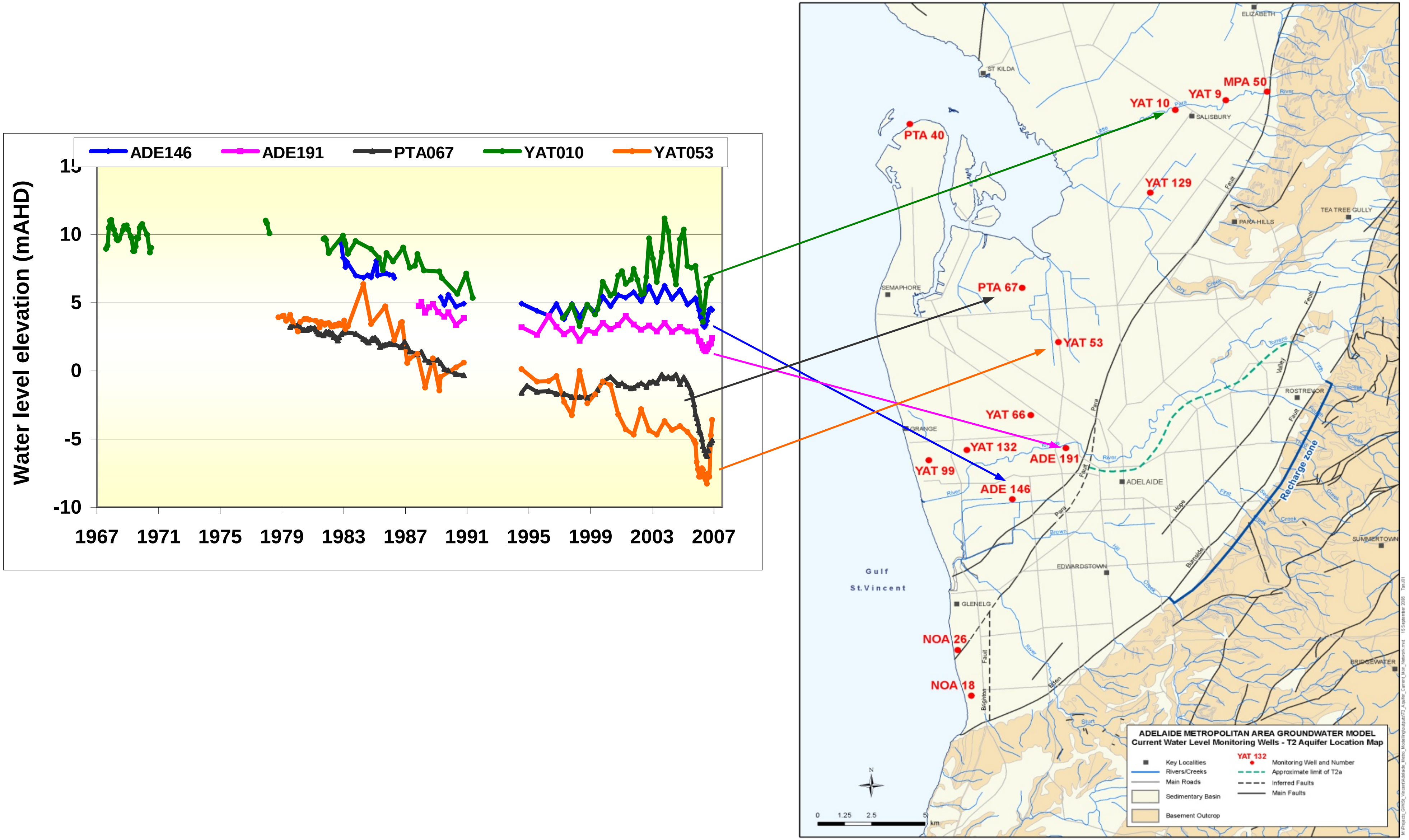


Figure 19. Current T2 aquifer monitoring wells and representative hydrographs

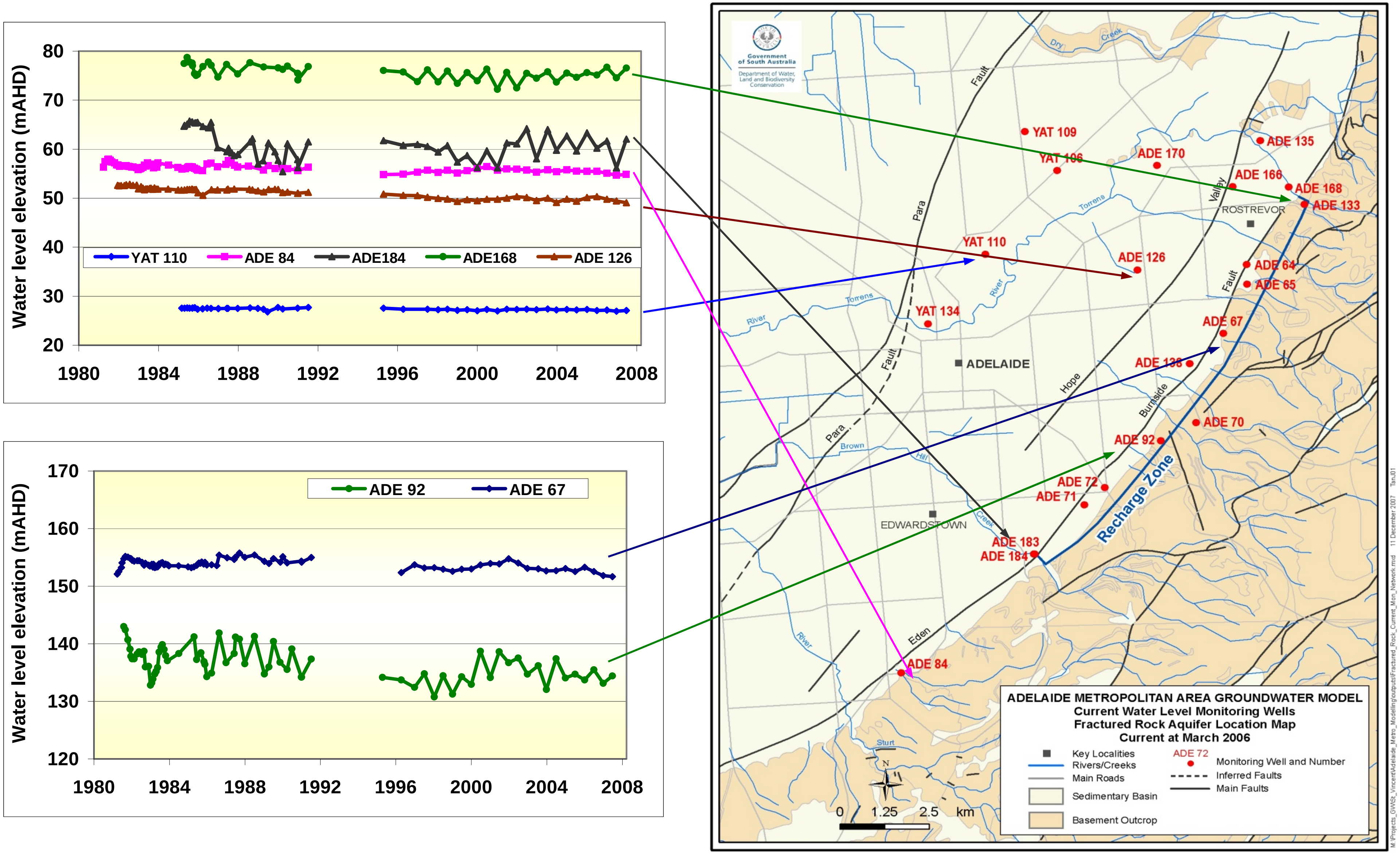


Figure 20. Current fractured rock aquifer monitoring wells and representative hydrographs

7.4 CURRENT T1 AQUIFER WATER BUDGET

The T1 aquifer has been recognised as the most productive aquifer in terms of salinity and yield, resulting in most groundwater extractions being obtained from this aquifer. The 1990s potentiometric surface shows that a permanent loss of head from the aquifer has occurred since 1936 (Gerges, 1999). The potentiometric surface has been severely modified by groundwater extractions and shows steep cones of depression in Zone 3 in summer, which recover towards their original levels during winter.

Outflow from the aquifer is solely by pumping for industry and irrigation since the hydraulic gradients do not permit outflow towards the Gulf.

Gerges (1999) calculated the water balance for two areas in Zone 3, based on the location of the major flow paths and extraction centres:

a. Metropolitan area outside the Northern Adelaide Plains PWA (Zones 3C, 3D, 3E and southern half of Zone 3B), and
b. Northern Adelaide Plains PWA south of Elizabeth (Zones 3A, northern half of Zone 3B).

7.4.1 METROPOLITAN AREA

The water balance of Metropolitan area was calculated by flow net analysis and is summarised in Tables 21. Based on summer and winter potentiometric surface maps, there is no lateral flow between the Metropolitan area and the PWA to the north. The only remaining outflow from the T1 aquifer is extraction during both summer and winter, which was calculated to be 3435 ML.

Table 21. Summary of water balance of Metropolitan area (ML)

	INFLOW		OUTFLOW	
Winter	Lateral throughflow	555	Winter extractions	685
	Downward leakage from Quaternary aquifer	55		
	Upward leakage from T2 aquifer	50		
	Total winter inflow	**660**	**Total winter outflow**	**685**
Summer	Lateral throughflow	2 560	Summer extractions	2 750
	Downward leakage from Quaternary aquifer	120		
	Upward leakage from T2 aquifer	120		
	Total summer inflow	**2 800**	**Total summer outflow**	**2 750**
	TOTAL ANNUAL INFLOW	**3 460**	**TOTAL ANNUAL OUTFLOW**	**3 435**

Inflow – Outflow = Change in storage

3460 ML – 3435 ML = 25 ML

Based on the estimated inflow and outflow the present day change in storage is +25 ML/year.

7.4.2 NORTHERN ADELAIDE PLAINS PWA (SOUTH)

Water balance of the Northern Adelaide Plains PWA (south) was also calculated by flow net analysis and is summarised in Tables 22 and 23.

Table 22. Summary of inflows to Northern Adelaide Plains PWA (south)

	INFLOW	
Winter	Lateral throughflow	720
	Downward leakage from Quaternary aquifer	65
	Upward leakage from T2 aquifer	75
	Total winter inflow	**860**
Summer	Lateral throughflow	985
	Downward leakage from Quaternary aquifer	125
	Upward leakage from T2 aquifer	130
	Total summer inflow	**1 240**
	TOTAL ANNUAL INFLOW	**2 100**

Extractions are the only significant outflow from the T1 aquifer in this area. In Zone 3A, Gerges (1999) considers the Carisbrooke Sand aquifer to be hydraulically connected with the underlying T1 aquifer, and the estimated 90 ML extracted from this aquifer is therefore considered part of the annual outflow from the T1 aquifer.

Outflow is summarised in Table 23.

Table 23. Summary of outflows from Northern Adelaide Plains PWA (south)

OUTFLOW	ML
Annual extractions from the T1 aquifer	1 995
Annual extractions from Carisbrooke Sand aquifer	90
TOTAL ANNUAL OUTFLOW	**2 085**

Inflow – Outflow = Change in storage

2100 ML/y – 2085 ML/y = 15

The total water budget of the whole study area is the sum of water balances for both the Metropolitan area and Northern Adelaide Plains PWA (south) :

Inflow – Outflow = Change in storage

(3460 + 2100 ML) – (3435 + 2085 ML)

5560 ML/y – 5525 ML/y = + 35

It should be stressed that this water balance applies to only one year in the current extraction regime where a new hydrogeological equilibrium has been established, which is very different from the pre-development regime. This small increase in storage may well have resulted in a small recovery in water levels.

8. KNOWLEDGE GAPS

Geological and hydrogeological investigations in the Adelaide Metropolitan area have been conducted for over more than five decades. However, there are still areas of uncertainty, particularly in deeper aquifers. These knowledge gaps are summarised below.

1. The geometry of the Tertiary aquifer systems is based on limited data:
    - Data is particularly limited in the Golden Grove Embayment where very few bores penetrated the full thickness of the Tertiary units. Consequently, the geometry and thickness of the T2a and T2b aquifers are mostly estimated and extrapolated.
    - In the Adelaide Plains sub-basin, very few bores intersect the full thickness of the T2 Aquifer in Zone 3, resulting in the thickness of this aquifer being almost entirely estimated.
2. Due to the limitations of the aquifer geometries, salinity records and their spatial and vertical distribution are also very limited. In particular, the spatial distribution of salinity data is inadequate for the T2a aquifer in the Golden Grove Embayment (Zone 2).
3. Discharge mechanisms beneath Gulf St Vincent are not well known. If the aquifers are bounded by impermeable sediments, upward leakage represents the only natural discharge from the system.
4. Lateral interconnection between aquifers across fault lines, and the extent to which these faults exert control on groundwater flow are not well understood.
5. There is no information on hydraulic properties for the T1 aquifer in Zone 4A, and the T2a aquifer in the Golden Grove Embayment (Zones 2, 4 and 4A).
6. There is limited distribution of hydraulic property data on the T1 aquifer in Zone 4 (currently available from only two wells).
7. Historic groundwater abstractions are based solely on the 1982–84 water survey (Edwards et al, 1987). It is essential to have more accurate data on groundwater use.
8. The lateral inflow into the sedimentary aquifers from the fractured rock was estimated by flow net analysis. To date, there have been no other attempts to estimate this lateral recharge.

The numerical modelling exercise will highlight which of the above data limitations are more significant than others, and will help to prioritise future investigations.

9. RECOMMENDATIONS

Groundwater level monitoring is currently conducted on a six monthly basis. It would be beneficial to monitor water level fluctuations on a quarterly basis because of the industrial nature of groundwater abstractions.

The existing monitoring network needs to be reviewed and assessed, and recommendations made for the upgrade of the network (rehabilitation, backfilling, new wells).

Salinity monitoring and regular reviews of sampling trends, are necessary in order to enable more vigorous management of the resource. Improved spatial distribution and more sampling sites across different zones are required.

Annual salinity sampling of each licenced well should be undertaken to monitor salinity trends.

Further investigation to assess salinity and yield of the T2a aquifer in the vicinity of the Para Fault Splinter block might be warranted, together with its possible hydraulic lateral continuity with the T2 aquifer.

An aquifer test is recommended to gain a better understanding of hydraulic connectivity between the T1 aquifer and the Carisbrooke Sand aquifer in the Little Para River area. There are three monitoring wells in this area which are completed in the T1 Aquifer (MPA 54, 55) and the Carisbrooke Sand Aquifer (MPA 57).

The drilling and sampling of nested piezometers is recommended in zones where aquifer interconnections are not well understood, such as near the Torrens River.

GLOSSARY

Act (the) — In this document, refers to the *Natural Resources Management (SA) Act 2004,* which supercedes the *Water Resources (SA) Act 1997*

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

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

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

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

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

ASR — Aquifer Storage and Recovery; involves the process of recharging water into an aquifer for the purpose of storage and subsequent withdrawal; also known as aquifer storage and retrieval

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

Artificial recharge — The process of artificially diverting water from the surface to an aquifer; artificial recharge can reduce evaporation losses and increase aquifer yield; see also 'natural recharge', 'aquifer'

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

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

Bore — See 'well'

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

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

Conjunctive use — The utilisation of more than one source of water to satisfy a single demand

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

Domestic purpose — The taking of water for ordinary household purposes; includes the watering of land in conjunction with a dwelling not exceeding 0.4 hectares

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

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

EPA — Environment Protection Authority (Government of South Australia)

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

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

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

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

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

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

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

NRM — Natural Resources Management; all activities that involve the use or development of natural resources and/or that impact on the state and condition of natural resources, whether positively or negatively

Permeability — A measure of the ease with which water flows through an aquifer or aquitard, measured in m^2/d

Potable water — Water suitable for human consumption such as drinking or cooking water

Potentiometric head — The potentiometric head or surface is the level to which water rises in a well due to water pressure in the aquifer, measured in metres (m); also known as piezometric surface

PWA — Prescribed Wells Area

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

Reticulated water — Water supplied through a piped distribution system

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

Stormwater — Run-off in an urban area

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

Water-use year — The period between 1 July in any given calendar year and 30 June the following calendar year; also called a licensing year

Well — (1) An opening in the ground excavated for the purpose of obtaining access to underground water. (2) An opening in the ground excavated for some other purpose but that gives access to underground water. (3) A natural opening in the ground that gives access to underground water

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Adelaide Metropolitan Area Groundwater Modelling Project

Volume 2:

Numerical model development and prediction run

Kwadwo Osei-Bonsu and Steve Barnett

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EXECUTIVE SUMMARY

In order to effectively manage the groundwater resources in the two main Tertiary aquifers (T1 and T2 aquifers) beneath the Adelaide Metropolitan Area, the Adelaide and Mount Lofty Ranges Natural Resources Management Board (AMLRNRMB) engaged the Department of Water Land and Biodiversity Conservation (DWLBC) to develop and construct a groundwater flow simulation model.

This report documents the development of a three-dimensional groundwater flow model using MODFLOW-2000. The model incorporates a revised interpretation of the hydrostratigraphy, and latest available information on the hydraulic properties. It is constructed with four layers simulating the shallow Quaternary sediments, the two Tertiary aquifers, and the confining layer separating the two aquifers. The grid size is a rectangular 100 m by 100 m.

The lateral extend of the modelled area is delineated by the faulted margin with the fractured rock aquifers of the Mt Lofty Ranges, a groundwater flow divide to the north, and an imaginary lateral discharge boundary 5 km out into Gulf St Vincent.

The steady-state model has been calibrated to conditions prior to significant groundwater withdrawal (pre-development conditions). Although the steady-state model is well calibrated, the subsequent transient model calibration was adequate but less accurate due to inaccuracies in the historical pumping data. In the T1 aquifer, a good match was obtained with water level trends and the recovered water level elevations.

A prediction run of future demands on the two aquifers was carried out using volumes requested on licence applications from existing groundwater users in the Central Adelaide Prescribed Wells Area. For the T1 aquifer, there was little change between the summer potentiometric surfaces for 2008 and 2030, with the important exception of the Thebarton area, just to the west of the city centre.

Here, the maximum drawdown increased from –35 to –110 m AHD, resulting in the potentiometric surface permanently falling below the top of the T1 confined aquifer, a situation which is not considered sustainable. Clearly, the demand of 1600 ML/yr in the Thebarton area is beyond the capacity of the resource.

There are no major increases in modelled drawdown in the T2 aquifer, however the extractions that caused the sudden increase in the observed drawdowns to the north in the Dry Creek area in recent years need to be included in future model runs.

A recalibration of the model should be carried out when metered extraction volumes become available over most of the model area.

1. INTRODUCTION

The increasing cost and restrictions on the availability of reticulated water has made the deep aquifers beneath the Adelaide Metropolitan Area very attractive for industrial use, and for the irrigation of recreational open spaces by councils, sports clubs and schools. The increase in groundwater extractions since the 1990s has led to the development of permanent cone of depressions in the north of the study area (Zulfic and Barnett, 2009).

In order to effectively manage the groundwater resources in the two main Tertiary aquifers (T1 and T2 aquifers) beneath the Adelaide Metropolitan Area, the Adelaide and Mount Lofty Ranges Natural Resources Management Board (AMLRNRMB) engaged the Department of Water Land and Biodiversity Conservation (DWLBC) to develop and construct a groundwater flow simulation model.

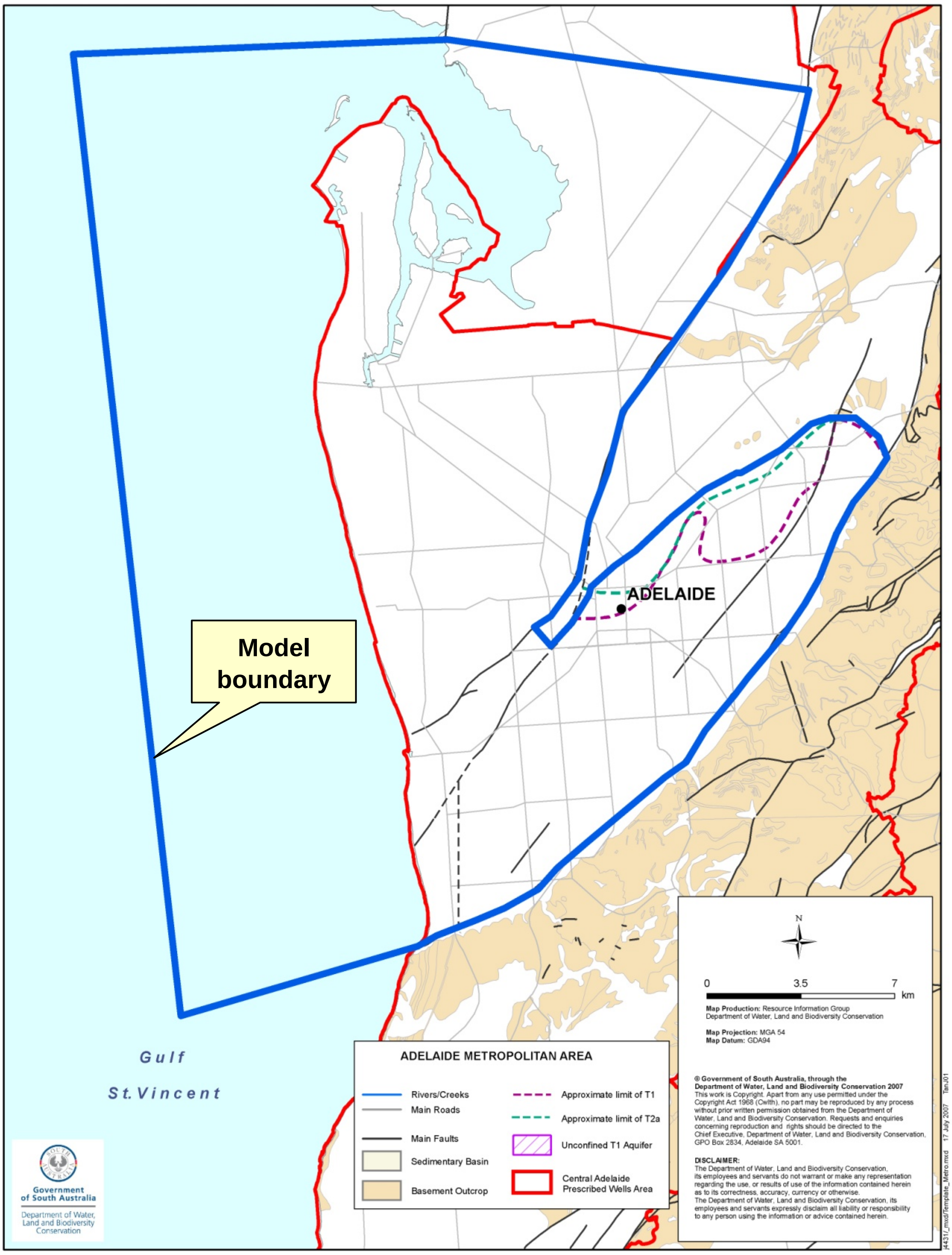
The model will be a very useful management tool which can be utilised ;

- To determine the critical factors affecting the responses of the Tertiary aquifers to stresses (extraction and injection)
- To provide a better understanding of groundwater flow in the T1 and T2 aquifers
- To investigate groundwater flow paths for the purposes of quantitatively determining the inter-zone and inter-aquifer flows
- To investigate the impact of future groundwater withdrawal from T1 and T2 aquifers for better management of the resources
- To provide predictive tool to understand well interference under different groundwater use scenarios
- To provide a tool to be use to optimize the allocation (distribution) of new wells and pumping volumes for sustainable use of the groundwater resources

To assist in the formulation of the conceptual model, a review of the hydrogeology of the study area was carried out (Zulfic and Barnett, 2009). New data from recent investigations resulted in several revisions to the hydrogeological framework proposed by Gerges (1999).

This report describes the model construction and an initial prediction run using the volumes of extraction applied for by existing groundwater users under the Prescription process. The prediction ran from 2008 until 2030.

The boundary of the Central Adelaide Prescribed Wells Area and the model extent are shown in Figure 1.



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

Map Projection: MGA 54
Map Datum: GDA94

Figure 1. CAGA boundary and model boundary

2. MODEL CONSTRUCTION

The code selected for this study is MODFLOW-2000 (McDonald and Harbaugh, 1988). MODFLOW-2000 is a 3-dimensional, finite-difference, block-centred, saturated groundwater flow code which is supported by boundary conditions packages to handle flow the processes such as lateral recharge and discharge, and extraction and injection via wells. MODFLOW is well documented and is the most widely accepted groundwater flow code.

GMS is a comprehensive MODFLOW interface that was used in this exercise that provides tools for every phase of groundwater simulation including site characterisation, model development, post-processing, calibration and visualization. Using GMS, models can be defined and edited at conceptual model level or on a cell-by-cell basis at the grid level. In addition to MODFLOW, GMS has interfaces to solute transport and particle tracking models (MODPATH, MT3DMS, RT3D, and VS2D).

The fundamental step in this model construction was the development of a GMS borehole information system. Geological log data from about 200 wells located in the Adelaide Metro and NAP area were analysed to develop various hydrostatigraphic units. The top and bottom elevation of these units were mapped to create a 3D hydrostratigraphy model using the 'Solid' module of GMS. The 'Solids' thus created were used to define the elevations of the various layers for the MODFLOW model.

MODFLOW-2000 requires a rectangular grid made up of rows and columns. The model origin is located at coordinates E 243393 and N 6134247, with grids orientated at 315^{o} to be consistent with the alignment of the lateral flow boundaries, and to allow cell faces (at the north and south boundaries) to be generally perpendicular to the regional flow direction. The model has 467 rows and 368 columns with 100 x 100 m grids.

2.1 CONCEPTUALISATION OF THE GROUNDWATER FLOW SYSTEM

The conceptualisation of the flow of groundwater in the study area was based on the considerable quantity of available information on all aspects of the hydrogeology of the area. The steps adopted in the development of the flow concept included definition of aquifers and confining units, identification of sources and sinks for groundwater, and delineation of the hydrogeologic boundaries encompassing the study area:

Essentially, groundwater recharges the Tertiary sedimentary aquifers from the fractured rock aquifers to the east, and flows in a southwesterly direction where it discharges beneath the ocean. Within the Tertiary aquifers, the groundwater flow path is controlled by the structures (faults) within the area, the hydraulic head distribution, connectivity of layers and the permeability variation within the aquifers. The flow paths as well as areas of higher transmissivity, can be delineated by areas of low salinity groundwater that have been recharged laterally from the fractured rock aquifers.

There have been significant changes in regional flow directions in the aquifers due to recent increases in pumping from both the T1 and T2 aquifers (Zulfic and Barnett, 2009).

2.2 EXTENT

The model boundaries were defined on the basis of structural and hydrogeologic boundaries. Essentially, the modelled area reflects the areal extent of the T1 and T2 aquifers. The model area is bounded laterally by:

The vertical boundaries along the southern and eastern limits of the model area correspond to the boundaries where the sediments abut the fractured rocks (which coincide with the Eden-Burnside and Para Faults).

The vertical boundary in the north of the model area corresponds to a groundwater divide representing the “stagnation” zone between two cones of depression located in the north of the model area.

The vertical boundary in the west of the model area corresponds to discharge zone beneath the ocean floor.

The upper boundary is defined by the ground surface elevation and the lower boundary by the base of the T2 aquifer.

2.3 MODEL LAYERS

Consistent with the model hydrostratigraphy described in Zulfic and Barnett (2009) and the conceptual flow model detailed above, the study area was divided vertically into four model layers. MODFLOW-2000 numbers layers from top to bottom and this is the order by which each layer was represented.

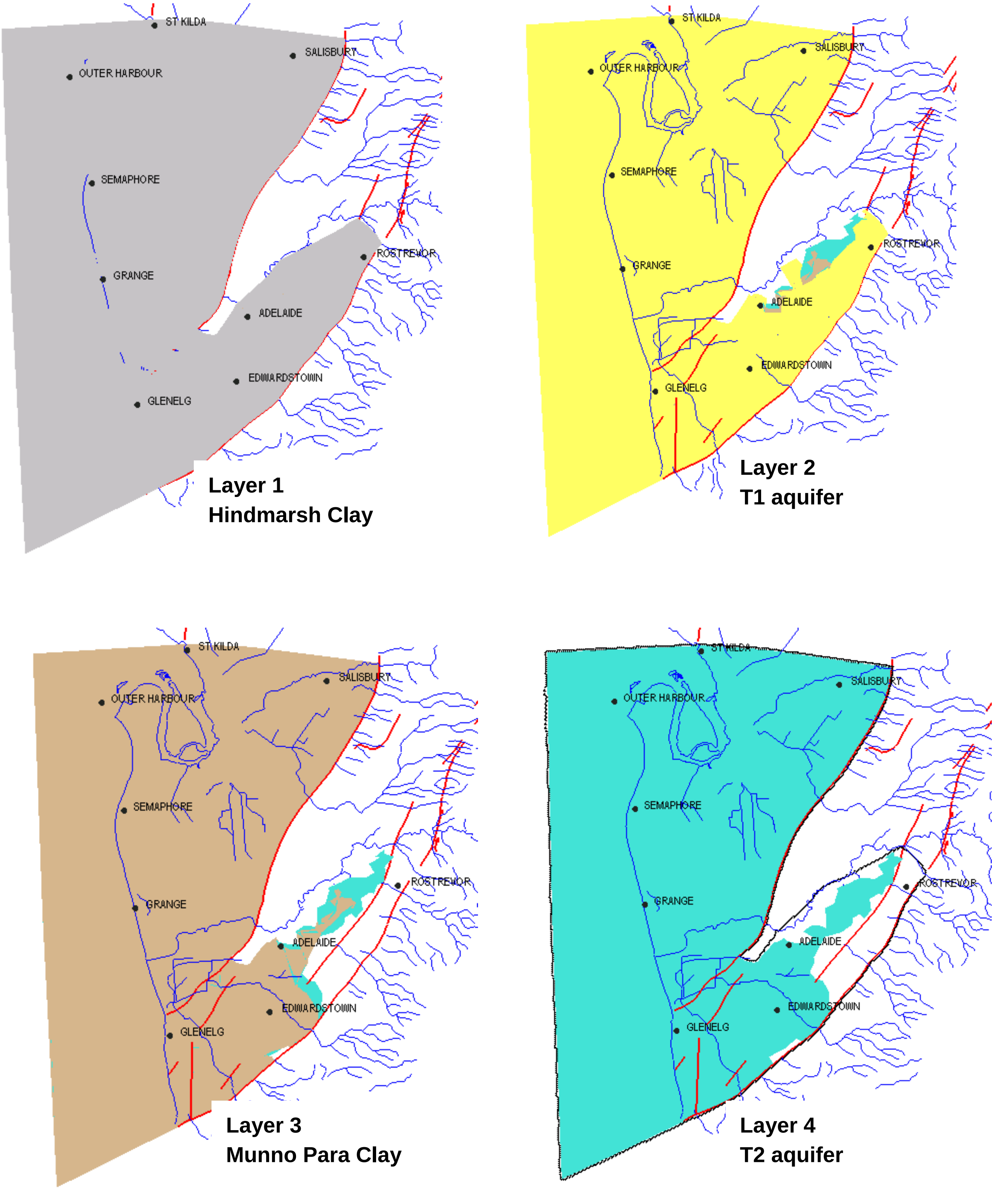
Layer 1 is the Hindmarsh Clay;

Layer 2 is the T1 aquifer;

Layer 3 is the Munno Para Clay confining layer and

Layer 4 is the T2 aquifer.

The extent of the various layers is shown in Figure 2, whilst the elevation of the various layers (m AHD) is presented in Figure 3.



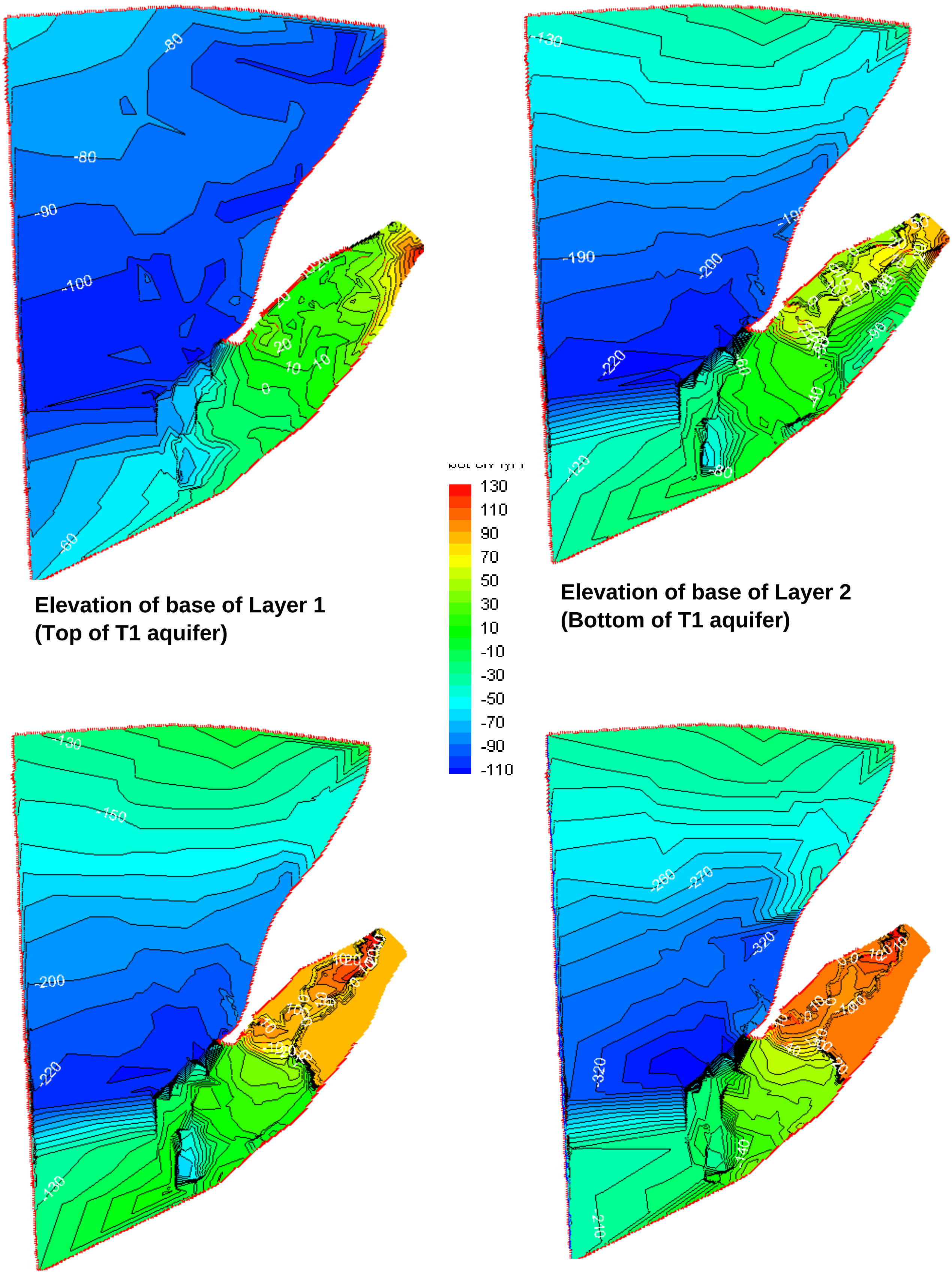
Layer 1
Hindmarsh Clay

Layer 2
T1 aquifer

Layer 3
Munno Para Clay

Layer 4
T2 aquifer

Figure 2. Extent of model layers



Elevation of base of Layer 1
(Top of T1 aquifer)

Elevation of base of Layer 2
(Bottom of T1 aquifer)

Elevation of base of Layer 3
(Top of T2 aquifer)

Elevation of base of Layer 4
(Bottom of T2 aquifer)

Figure 3. Elevation of model layers

2.4 BOUNDARY CONDITIONS

The modelled area is not a closed hydrogeologic system. To represent this limitation, model boundary conditions were used to account for the flow to and from areas beyond the extent of the model area. The perimeter of the model is bounded by a combination of constant head boundaries, variable flux or general head boundaries, and no-flow boundaries

2.4.1 LATERAL FLOW BOUNDARIES

The Eden-Burnside and the Para Faults form the southern and eastern flow boundaries where lateral inflows (recharge) occur, and are simulated as specified heads. Because the water levels in the fractured rock aquifers adjacent to the faults lines show little variation, the heads at these boundaries are assumed to be constant throughout the simulation period for both the T1 and T2 aquifers (Fig. 4).

Lateral groundwater outflow (discharge) is assumed to take place beneath the ocean floor and consequently, a discharge boundary was assigned to the western boundary of the model. This boundary was simulated as constant head for both the T1 and T2 aquifers.

From a review of both predevelopment and current potentiometric surface maps, it was concluded that the northern boundary is coincident with the groundwater flow direction and therefore no-flow boundaries were applied in both aquifers.

2.4.2 VERTICAL FLOW BOUNDARIES

The upper boundary of the Tertiary aquifer system is formed by the low permeability Hindmarsh Clay (Layer 1), which are present over all of the modelled area. It is assumed that these clayey sediments impede vertical recharge into the Tertiary aquifers from rainfall and also from surface water bodies (rivers, irrigation return flows). Based on this assumption, the upper boundary was assumed as a no-flow boundary.

The lower flow boundary was defined as the contact between the T2 aquifer and the underlying low permeability clay/silt deposits of the Chinaman Gully Formation which extend over the whole modelled area. Because these low permeability deposits impede vertical flow, the bottom of Layer 4 (T2 aquifer) was assigned a no-flow boundary.

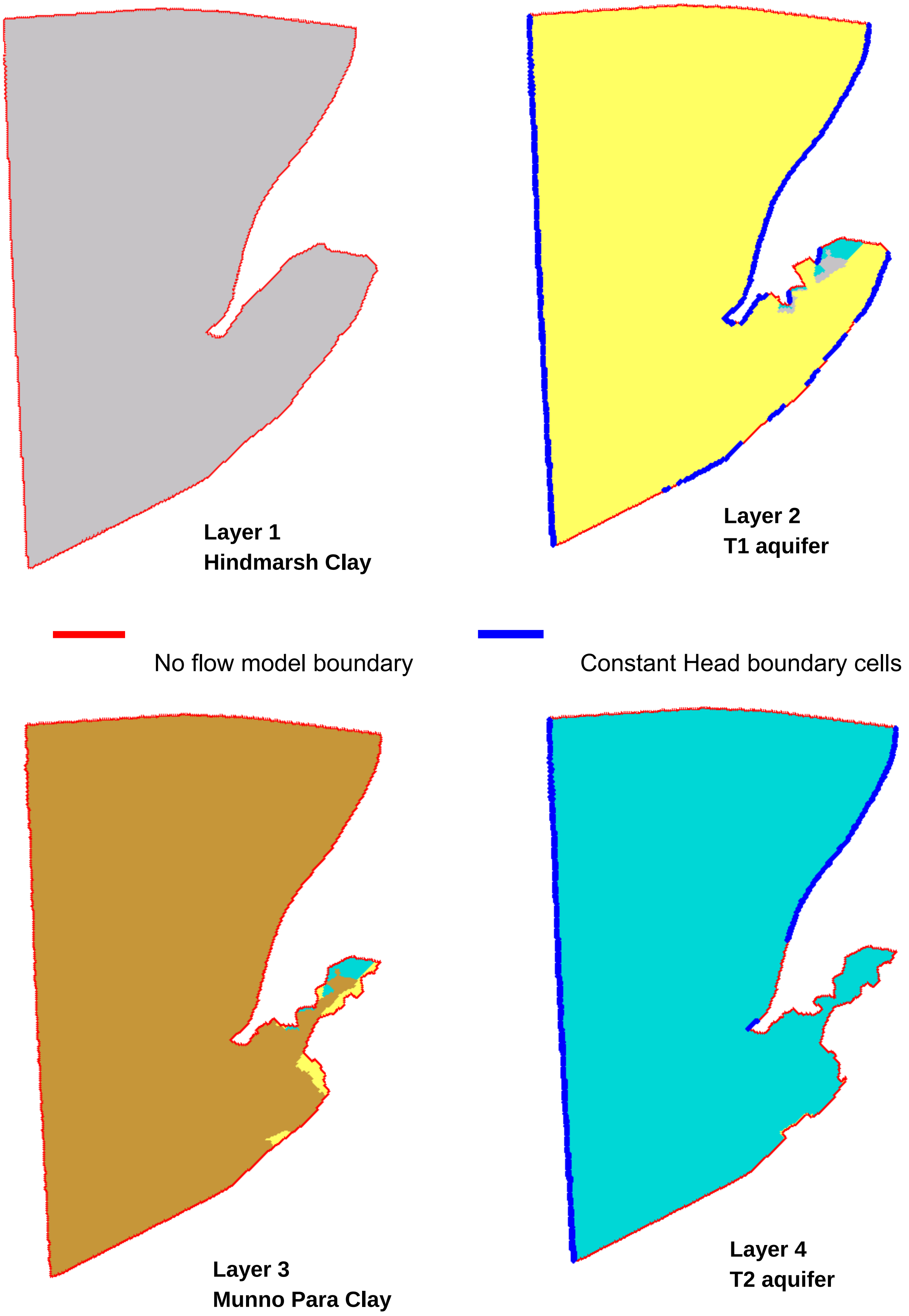


Figure 4. Model boundary conditions

2.5 MODEL HYDRAULIC PARAMETERS

The aquifer characteristics that control the capacity of the aquifer to store and transmit water are the hydraulic conductivity, specific yield, specific storage, and storage coefficient. For a steady-state model, the parameters required are horizontal and vertical hydraulic conductivities for the model layers, while for the transient simulations, both hydraulic conductivity and storage coefficient values are required.

Information on the hydraulic conductivity and storativity of the aquifer system in the study area is based on studies undertaken by Hodgkin (2004). Hodgkin compiled horizontal hydraulic conductivity values from several sources for the T1 and T2 aquifers in the Adelaide Metropolitan Area. The spatial distribution of these values as determined from aquifer tests is presented in Figure 5.

Most of the values for the T1 aquifer are evenly distributed in the central part of the model area, but there is little or no horizontal hydraulic conductivity data in the northeast and northwestern parts of the modelled area.

A summary of the statistical analysis of the horizontal hydraulic conductivity values for the two aquifers is given in Table 1. The table presents the number of data measurements and the mean, median and range of hydraulic conductivity values. The range for the T1 aquifer is 0.15 to 8.8 m/d and 0.97 to 9.6 m/d for the T2 aquifer.

Table 1. Summary of statistics for aquifer horizontal hydraulic conductivity

Layer	Hydrogeologic unit	Count	Minimum m/d	Maximum m/d	Range m/d	Median K (m/d)	Mean K (m/d)
2	T1 aquifer	22	0.15	8.88	8.73	2.04	2.46
4	T2 aquifer	7	0.97	9.6	8.63	1.85	2.81

In this modelling exercise, the hydraulic properties are constant within any given grid cell which can vary in thickness, and in area from 1 to 2 x 10^4 m^2. The distribution of initial horizontal hydraulic conductivity values in the model layers are shown in Figures …. In areas lacking aquifer test values, the lithology and depositional environment were used to estimate the initial values (which were later modified when necessary during the model calibration process). A horizontal anisotropy ratio of 1:1 and a vertical anisotropy ratio (K_h/K_v) of 10:1 were used.

When considering the confining layers, the vertical hydraulic conductivity is important as it controls the rates of leakage between aquifers. Table 2 displays values obtained from testing core samples.

Table 2. Vertical hydraulic conductivity values for confining layers

Layer	Confining layer	Range m/d
1	Hindmarsh Clay	5.0×10^{-7} to 2.3×10^{-3}
3	Munno Para Clay	2.6×10^{-7} to 1.7×10^{-5}

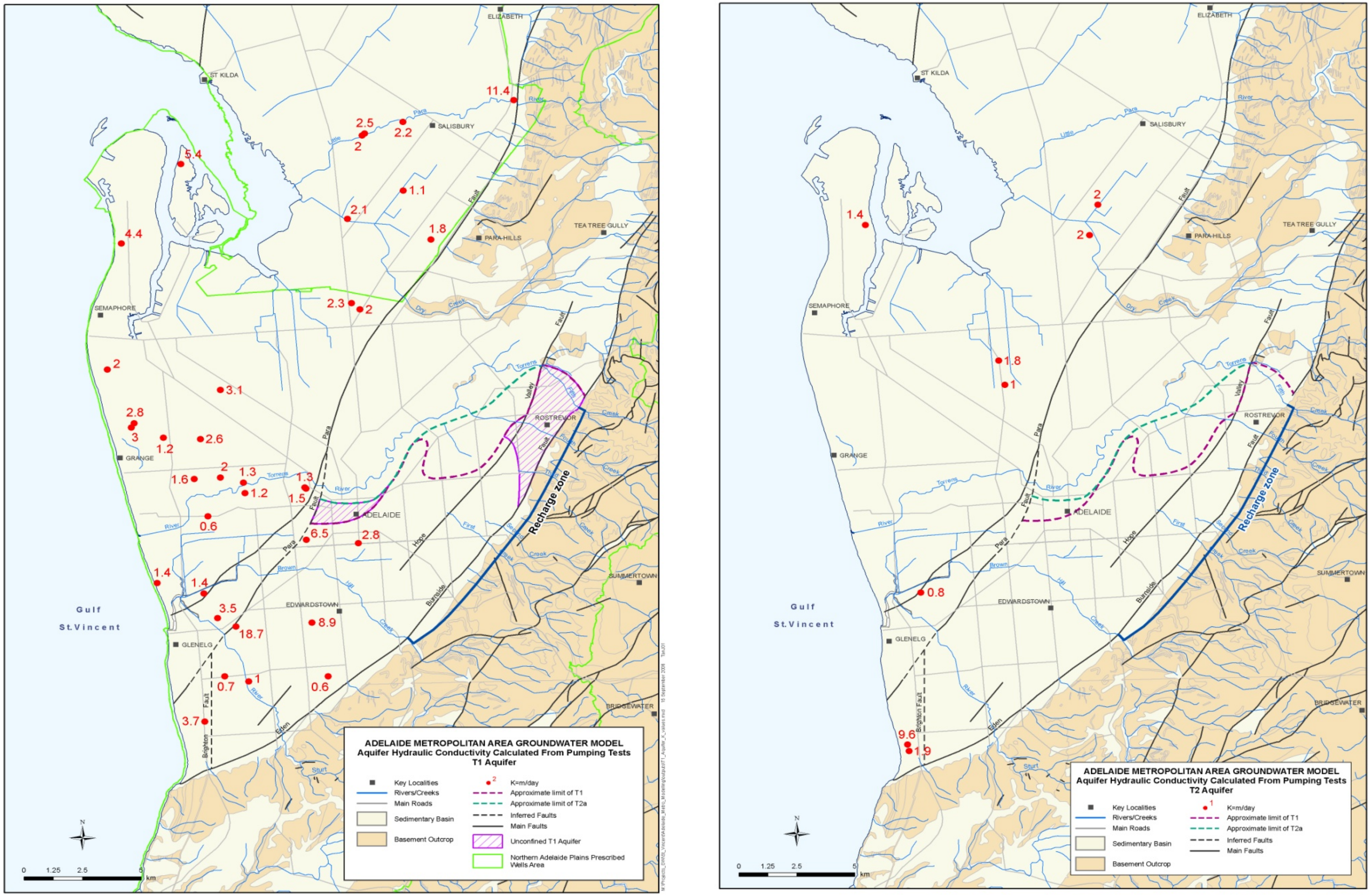


Figure 5. Hydraulic conductivity values for T1 and T2 aquifers

2.6 PRE-DEVELOPMENT CONDITIONS

Although pumping from the Tertiary aquifers for the reticulated supply and irrigation began in the mid 1940s, little water level data exists prior to 1940. Few of the early water level measurements available in the study area are considered to be representative of predevelopment conditions, and there are insufficient to develop water level elevation contours. Careful selection of water level measurements prior to development (before 1940 for the T1 aquifer, and before 1970 for the T2 aquifer) resulted in a total of 162 values that could be used as point targets for calibration of the steady state model.

Figure 6 presents the modelled pre-development potentiometric surface elevation contours for both the T1 and T2 aquifers, which were used as the initial conditions (starting heads) for the transient model.

2.7 COMPARISON WITH PREVIOUS MODELS

The MODFLOW model developed by Gerges comprised ten layers with a grid size of 570 x 680 m. The ten layers comprised four Tertiary aquifers, five intervening confining layers and the basement fractured rock aquifer. Calibration difficulties were encountered during historical periods of heavy pumping during drought.

The REM MODFLOW model incorporated a significant area of the Mt Lofty Ranges, the Northern Adelaide Plains Prescribed Wells Area and the Adelaide Metropolitan Area. It comprised six layers extending down to the base of the T2 aquifer, with a 500 x 500 m grid size. The modelling exercise was designed to test management options for the Northern Adelaide Plains Prescribed Wells Area, and to examine how various extraction regimes in the fractured rock aquifers would change inflows into the Tertiary aquifers.

The groundwater model described in this report has benefited from a detailed study of the hydrostratigraphy of the aquifer system and recent aquifer test information, to better define the geometry and hydraulic connection between individual hydrogeologic units. The differences between this model and previous models are:

The Quaternary Hindmarsh Clay and the thin interbedded aquifers contained within it, are all lumped together in Layer 1 because of the regional nature of the model. The Carisbrook Sand found below the Hindmarsh Clay in the northeast of the model area is also included in Layer 1, as no evidence of hydraulic connection with the underlying T1 aquifer was found. Previous models had assumed that such a connection did occur, and considered the Carisbrook Sand aquifer to be part of the T1 aquifer.

This model also incorporates new interpretations of the interaction between T1 and T2 aquifers. In other modelling work, the Para Fault Block was considered to constitute one aquifer. In this study, the T1 and T2 aquifers are recognised as distinct aquifers separated by a confining layer which are all continuous across the fault zone.

The undifferentiated sediments to the northeast of the city centre toward Rostrevor (Fig. 2) were treated as one aquifer and is considered part of T1 aquifer. Also, based on available borehole information and published reports, the Munno Para Clay confining layer and T2 aquifer are considered absent in the southeast section of the modelled area.

The horizontal grid discretization for this model (100 x 100 m) is much finer than in earlier models, allowing a more detailed representation of the aquifer geometry and better resolution of the impacts of extraction.

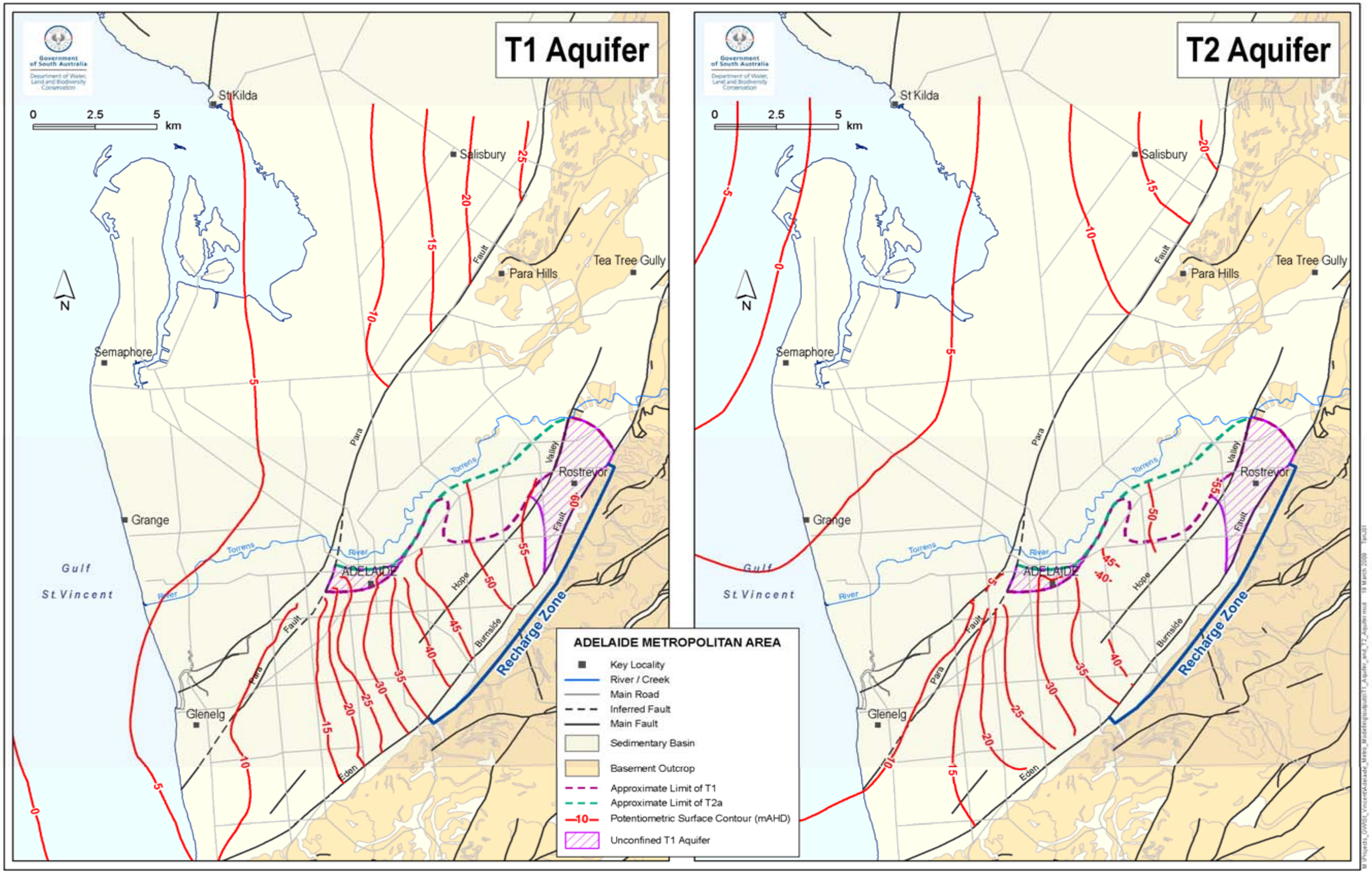


Figure 6. Pre-development potentiometric surfaces for T1 and T2 aquifers

3. MODEL CALIBRATION

The groundwater flow models were calibrated by adjusting the value and distribution of the model input parameters so that the resulting model output matched the measured water levels and other hydrologic observations within an acceptable level of accuracy. Changes to the hydrogeologic parameter values were evaluated during the calibration processes to confirm that the changes implemented were within the acceptable range of variability of the parameters. After each change in model parameter value, model output was generated and compared with measured data to evaluate the effect of the selected parameter.

The model accuracy was calculated using the root mean square error (RMSE) comparison between water level measurements and simulated water levels. Model accuracy is increased as RMSE approaches zero. Average model error (AVER) was also used during model calibration processes to evaluate model bias, which occurs when the differences between simulated and observed water levels is predominantly positive or negative.

Trial-and-error method was used in the model calibrations. As the models were constructed, assumptions were necessary to reduce the model instability. The model was initially simplified but as the calibrations proceeded, more complexity was systematically integrated into the model to improve the model output and to better represent the actual field conditions. The final steady-state model incorporates parameters that were modified during calibration of the transient model.

The models were considered calibrated when the following criteria were satisfied:

> The RMSE was equal to or less than 10% of the observed head range.
>
> The simulated groundwater potentiometric heads and lateral groundwater flow directions in the model compared favourably with those determined from water level measurements and published potentiometric surface maps of the T1 and T2 aquifers.
>
> The simulated transient water levels fluctuations throughout the transient calibration period closely resembled measured water levels fluctuations resulting from the effects of variable (pumping) stresses through time.

3.1 *STEADY-STATE MODEL CALIBRATION*

The steady-state model was calibrated using tested hydraulic conductivity values and observed water levels in both aquifers. Flow net calculations of lateral recharge and discharge values were also used as a guide. The measured horizontal hydraulic conductivity values were used as initial model values which were varied within a specified range of reasonable values to obtain as close a match as possible between observed and simulated groundwater levels. Observed values included water levels measured at 162 wells. Pumping discharge and recharge were not considered in the steady state model because it is represents conditions prior to significant use of the groundwater resources.

3.1.1 GROUNDWATER LEVELS

During the calibration process, improvements in the model output were evaluated by calculating the mean error (ME), the mean absolute error (MAE) and the root mean square error (RMSE) between the measured and simulated groundwater levels. Table 3 presents the calibration statistics.

Table 3. Calibration statistics for the steady-state model

Layer	Hydrogeologic unit	Mean Error (m)	Mean Absolute Error (m)	Root Mean Square Error (m)	Range in water heads (m)	RMS/Range %
2	T1 aquifer	0.012	0.242	0.327	60	0.54
4	T2 aquifer	-0.059	0.234	0.264	60	0.44

The calibration statistics shows the RMS of 0.296 (0.54%) and 0.284 (0.44%) for the T1 and T2 aquifers respectively are well within the widely accepted MDBC Modelling Guidelines recommendation of 5%.

The differences between the observed and model-calculated heads are called the absolute residuals. A positive residual indicates that the model has overpredicted the hydraulic head, while a negative residual indicates underprediction. A graphical representation of the comparison between observed and calculated heads at observation wells in the three aquifers located throughout the model domain is presented in Figure 7. As can be seen, there is a very good match with all points lying close to the 1:1 line.

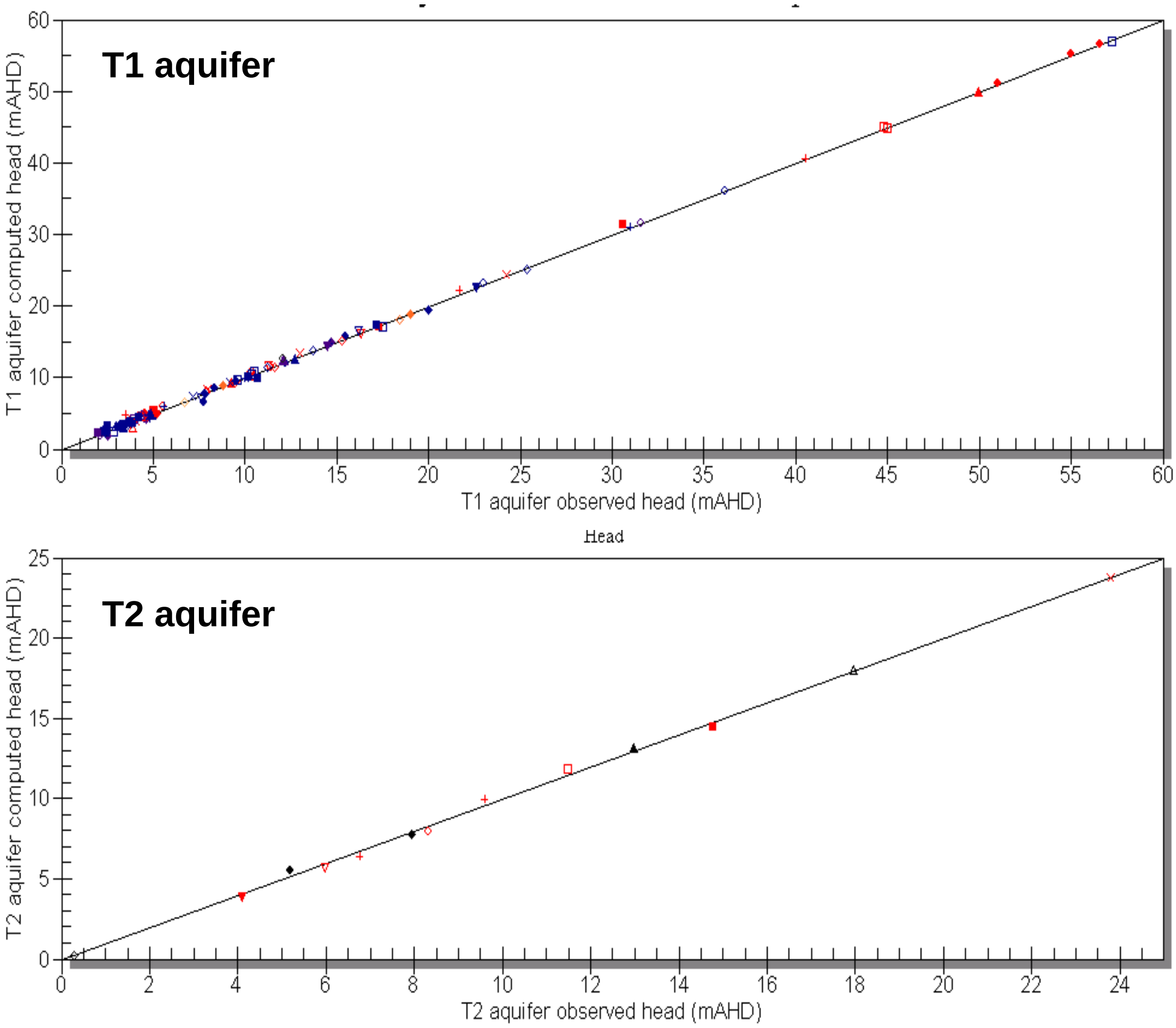


Figure 7. Computed vs observed head steady state calibration results

Figure 8 presents the residual (the difference between observed and calculated heads) plotted against the elevation of the water level at each observation well. Again, a very good calibration is indicated over most of the model domain.

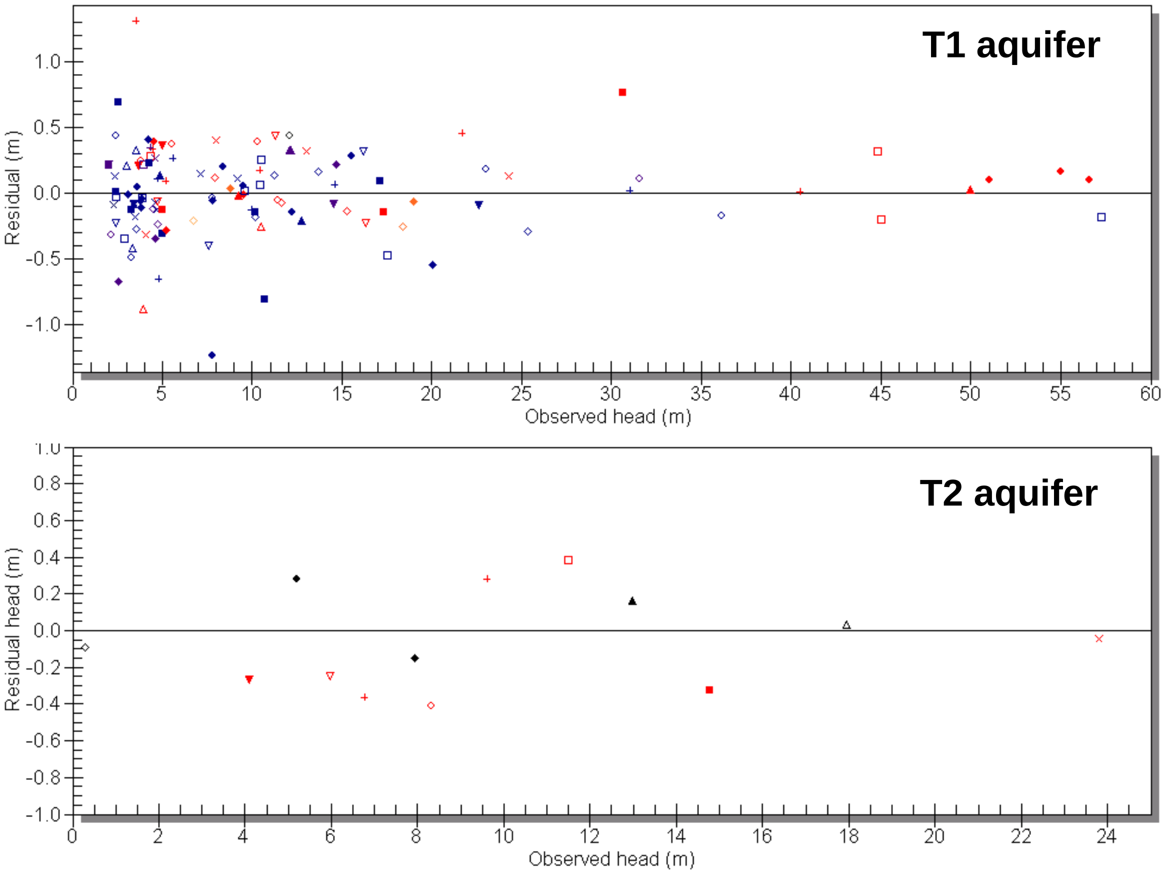


Figure 8. Residual vs observed head steady state calibration results

The residuals for the aquifers are mostly within a range of 0.5 m except for the observation wells listed in Table 4.

Table 4. Observation wells with residuals > 0.5m

Obswell	ADE001	ADE044	ADE180	PTA078	YAT052	NOA014
Residual	1.3	0.88	0.77	0.81	0.69	2.02

3.1.2 STEADY STATE SENSITIVITY ANALYSIS

A sensitivity analysis determines which parameters have the greatest effects on the modelling results, by varying the model input parameters by several orders of magnitude while the remaining model parameters were held at the calibrated values. The steady state model sensitivity was determined by varying the calibrated values of hydraulic conductivity (horizontal and vertical) for the T1 and T2 aquifers, and vertical hydraulic conductivity for the Munno Para Clay confining layer.

Figure 9 shows the sensitivity of Layers 2 and 4 to the horizontal hydraulic conductivity of Layer 2, and indicates that the change in head in the T1 aquifer is sensitive to horizontal hydraulic conductivity values of T1 aquifer when they are less than calibrated values. The model underpredicts the heads when the horizontal hydraulic conductivity values of T1 aquifer are underestimated. Similar sensitivity pattens are shown in for Layer 4.

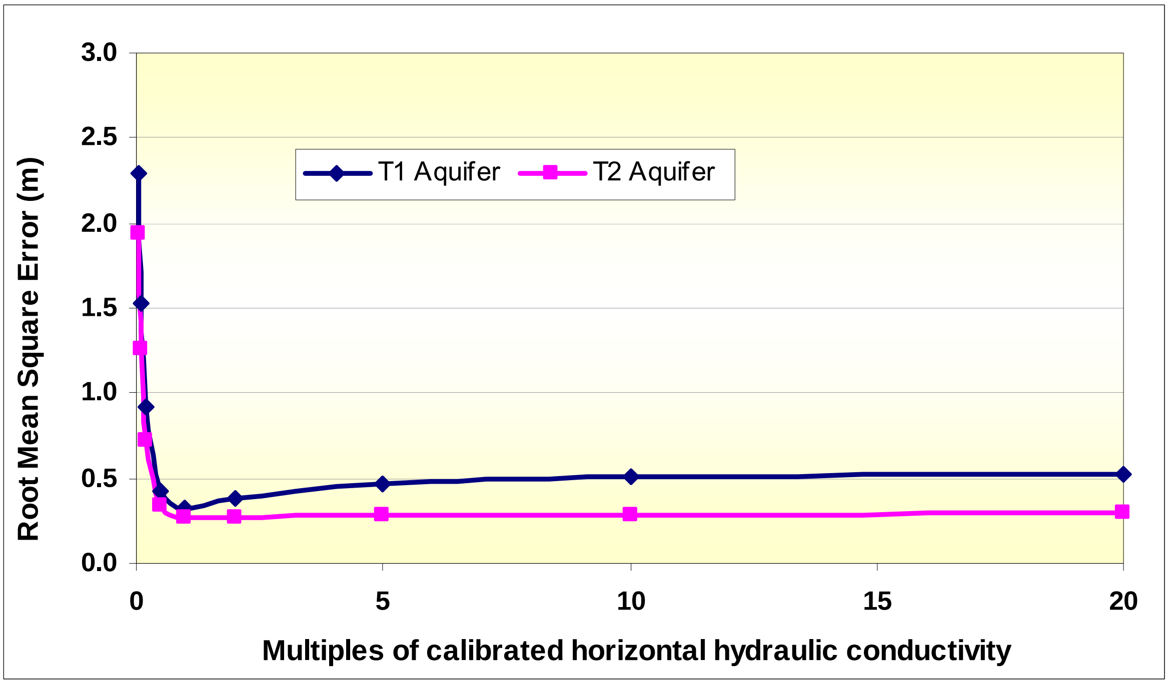


Figure 9. **Sensitivity analysis with respect to changes to calibrated horizontal hydraulic conductivity of T1 Aquifer**

The statistical errors as show in Table 5. The output is expressed in terms of Root Mean Square error (RMS) and the Mean Error (ME) between the calibrated simulated head and the sensitivity-simulated head.

Table 5. **Sensitivity analyses for varying Layer 2 horizontal hydraulic conductivity**

Multiples	**0.05**	**0.1**	**0.2**	**0.5**	**2.0**	**5.0**	**10.0**	**20.0**
Layer 2 ME (m)	-0.77	-0.45	-0.22	-0.06	0.00	0.03	0.04	0.05
Layer 2 RMS (m)	2.29	1.53	0.92	0.42	0.33	0.39	0.47	0.51
Layer 4 ME (m)	-0.86	-0.54	-0.28	-0.08	0.00	0.04	0.06	0.07
Layer 4 RMS (m)	1.94	1.26	0.72	0.33	0.26	0.27	0.28	0.29

The sensitivity of the vertical hydraulic conductivity of Layer 3 (Munno Para Clay confining layer) on hydraulic heads in Layers 2 and 4 is shown in Figure 10, and indicates that heads in the T1 and T2 aquifers are sensitive to values that are greater than the calibrated values, with the T2 aquifer heads more sensitive than those in the T1 aquifer. Overestimation of vertical hydraulic conductivity would have an impact on the water levels in both the T1 aquifer (slight overprediction) and T2 aquifer (underprediction), whilst underestimation would have negligible impact.

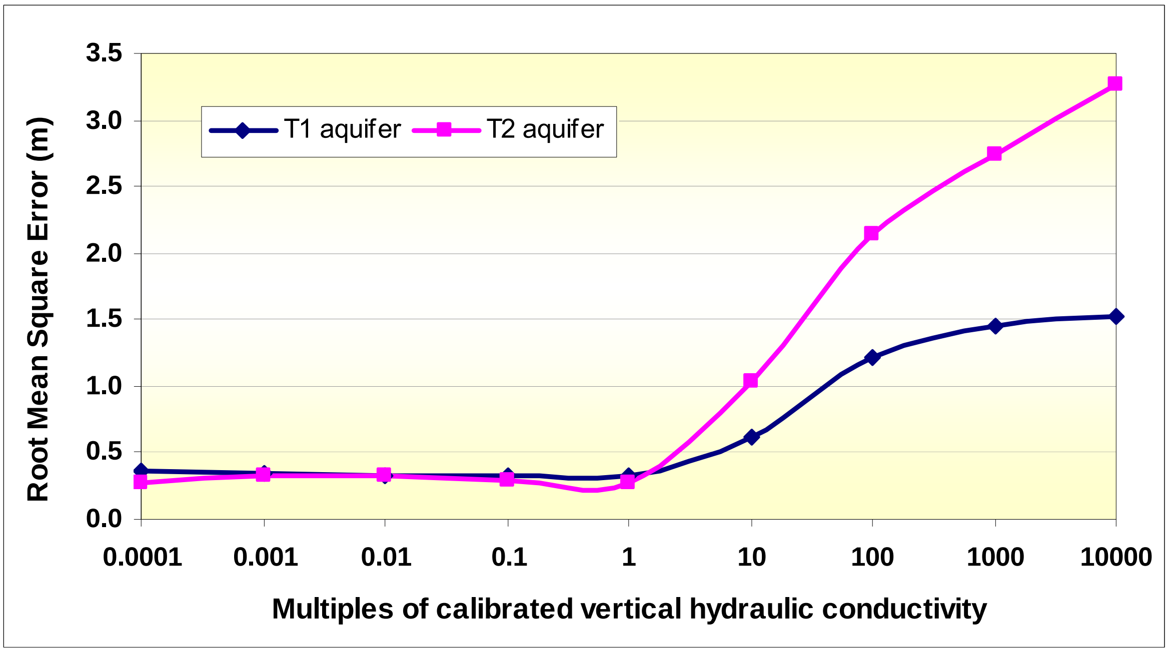


Figure 10. **Sensitivity analysis with respect to changes to calibrated vertical hydraulic conductivity of Munno Para Clay**

3.1.3 GROUNDWATER BUDGET

The overall mass balance calculated by the steady state model is given in Table 6 where the water budget is summarized in terms of rate in m^3/d. The overall mass balance error for the steady state simulation was 0%, within the accepted MDBC Modelling Guidelines recommendation of 1%.

Table 6. **Steady state groundwater budget (m^3/d)**

	T1 aquifer		**T2 aquifer**
Lateral inflow from hills	7073	Lateral inflow from hills	2028
Upward leakage from T2	600	Downward leakage from T1	1368
Downward leakage from HC	18	Upward leakage from base	0
TOTAL INFLOW	**7691**		**3396**
Lateral outflow to ocean	6305	Lateral outflow to ocean	2800
Upward leakage into HC	18	Upward leakage into T1	600
Downward leakage into T2	1368	Downward leakage into base	0
TOTAL OUTFLOW	**7691**		**3400**

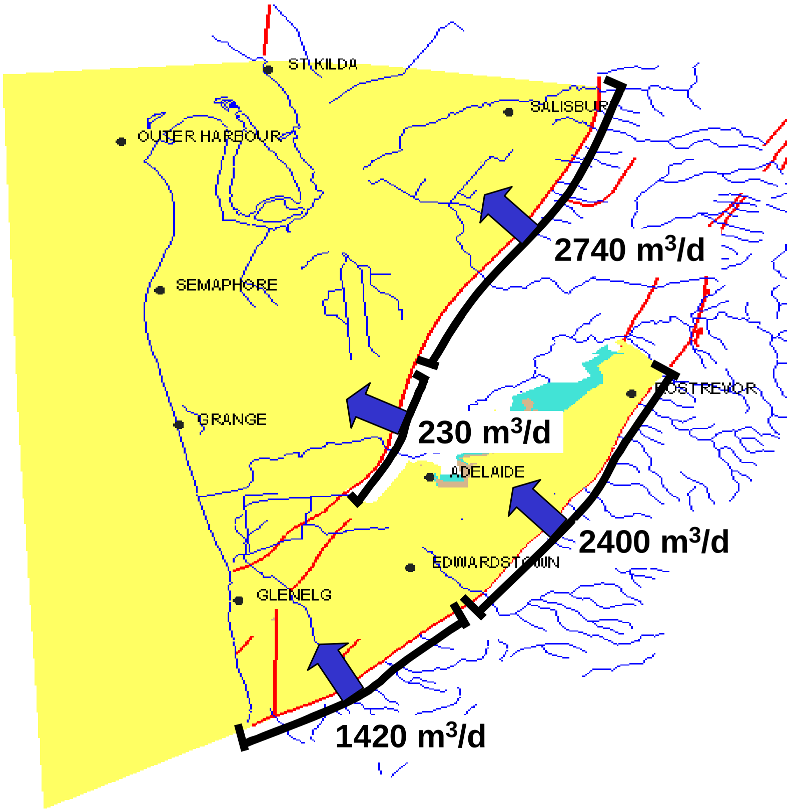


Figure 11. Modelled lateral inflows into the T1 aquifer

The model determined predevelopment lateral inflow from the fractured rocks along the Eden-Burnside Fault and Para Fault lines, with the Eden-Burnside fault zone contributing about 60% of the total inflow to the model (Fig. 11).

3.2 TRANSIENT CALIBRATION

The transient model used the steady state results as the initial conditions, and carried out a simulation from the predevelopment situation in 1940, through to 2006. The model was calibrated to changes in water levels in response to recharge and pumping, primarily by varying the storage properties within ranges of reasonable values. Each year was divided into two stress periods representing summer and winter seasons coinciding with the pumping and recovery periods. The winter stress period began in March/April and lasted for 155 days, with the summer stress period beginning in August/September and lasting 210 days.

The MODFLOW well-package was used to simulate extraction and injection via wells where specified flow boundary conditions were assigned for each stress period, for each active cell within which pumping is occurring. For each of the stress periods, only pumping rates were updated in the model.

The model was calibrated to simulate hydrologic conditions in the T1 and T2 aquifers. Historical water level measurements made at numerous observation wells completed in these aquifers during the transient calibration. The model generated water levels at the last time step of each stress period that were compared to the corresponding measured water levels in observation wells.

Because of large extractions in some areas, and unconfined conditions in part of the model area, the aquifers were simulated to allow for conversion from both confined and unconfined conditions. Consequently, values of both specific storage and specific yield were required for each aquifer.

Table 7 presents the transient calibration statistics.

Table 7. Calibration statistics for the transient model

Layer	**Hydrogeologic unit**	Mean Error (m)	Mean Absolute Error (m)	Root Mean Square Error (m)	Range in water heads (m)	RMS/Range %
2	T1 aquifer	2.35	5.20	8.04	78	10.3
4	T2 aquifer	3.77	4.84	7.07	65	10.9

The calibration statistics shows the RMS of 8.04 (10.3%) and 7.07 (10.9%) for the T1 and T2 aquifers respectively, are less impressive than the steady state calibration, but considering the large uncertainties in historical pumping volumes and hydraulic parameters, are considered reasonable.

A comparison of modelled and observed water levels is presented later in Figures 12 and 13, together with a discussion of the prediction results.

4. PREDICTION RUN

As part of the prescription process for the Central Adelaide Prescribed Wells Area, existing groundwater users were invited to apply for an allocation and nominate a volume required for their on-going extraction. These volumes were used as extraction rates for a prediction run from 2008 until 2030.

Tables 8 and 9 show the annual groundwater budgets for both aquifers at various rates of extraction. The natural discharge from the T1 aquifer to the ocean (Table 8) has decreased markedly as the extractions lower the potentiometric surface and reduce the flow gradients toward the coast. However, discharge is still occurring and the risk of sea water intrusion is minimal (considering the 50 m of clay between the ocean and the aquifer). The decrease in pressure levels has caused an increase in leakage into the T1 aquifer from both the overlying Hindmarsh Clay and the underlying T2 aquifer in areas of concentrated pumping. Of most concern is the downward leakage because of the higher groundwater salinities in the overlying Hindmarsh Clay.

Table 8. T1 aquifer annual groundwater budget (ML)

	Pre-development	2008	2030
Lateral inflow from hills	7073	5028	6619
Upward leakage from T2	600	1127	1417
Downward leakage from HC	18	2252	2506
TOTAL INFLOW	**7691**	**8407**	**10542**
Groundwater extraction	0	7043	9281
Lateral outflow to ocean	6305	623	507
Upward leakage into HC	18	33	40
Downward leakage into T2	1368	582	575
TOTAL OUTFLOW	**7691**	**8281**	**10403**

The more modest withdrawals from the T2 aquifer compared to the T1, resulted in a less significant reduction in outflows to the ocean (Table 9). The reduction in pressure levels due to pumping has increased inflows from the fractured rock aquifers, with the degree of increase proportional to the increase in extraction. Downward leakage from the T1 aquifer has decreased due to pumping in that aquifer lowering the pressure levels and decreasing the downward head difference that is driving the leakage.

Table 9. T2 aquifer annual groundwater budget (ML)

	Pre-development	2008	2030
Lateral inflow from hills	2028	2287	2391
Downward leakage from T1	1368	596	562
TOTAL INFLOW	**3396**	**2883**	**2953**
Groundwater extraction	0	1824	1257
Lateral outflow to ocean	2800	567	605
Upward leakage into T1	600	846	457
TOTAL OUTFLOW	**3400**	**3237**	**2319**

Figure 12 presents the comparison of modelled and observed water levels during the transient calibration for the T1 aquifer, together with the prediction hydrographs for selected observation wells. The observed water levels are shown in blue, with the upper and lower bounds of the transient calibration water levels up until 2009 shown in pink. The prediction results to 2030 are shown in red.

In general, the transient calibration results are good, with a good match with overall water level trends and the recovered water levels in September (which is important from a long term sustainability perspective). There are however, some differences with the magnitude of the seasonal drawdown which reflects the volume of extractions. As stated earlier, the estimates for historical pumping have large uncertainties, and recalibration of the model should be carried out after several years of metered extraction (as required by a licence condition) has been documented.

The prediction results assume a constant extraction rate and show a gradual falling trend that is typical of a modelled confined aquifer, but in reality is rarely seen due to annual variations in the extraction rates. Most show a continuation of current trends, with the exception of ADE 2 which shows an increase in seasonal drawdown due to increased demand in the Thebarton area.

The T2 aquifer results (Fig. 13) show a different response to extractions because most pumping from the T2 aquifer is for industrial purposes continuously all year, compared to the summer dominant irrigation extractions from the T1 aquifer. The transient calibration is not as good as the T1 aquifer because of the lack of aquifer parameter data, and the large uncertainties in historical pumping volumes.

There is reasonable agreement with trends in several wells, but of concern is the dramatic decline in T2 pressure levels in recent years in the vicinity of Dry Creek in the north of the model area. It appears that the increase in extractions responsible was not included in the transient model, and appears to be much higher than the rate assumed to represent future demand.

Comparison of the modelled T1 aquifer potentiometric surfaces for March (maximum drawdown) in 2008 and 2030 (Fig. 14) shows an intensification of drawdown in the Thebarton area, and a broadening of the drawdown cone to the northwest. Here, the maximum drawdown increased from –35 to –110 m AHD, resulting in the potentiometric surface permanently falling below the top of the T1 confined aquifer, a situation which is not considered sustainable. Clearly, the demand of 1600 ML/yr in the Thebarton area is beyond the capacity of the resource. Elsewhere, there was very little change between 2008 and 2030.

Figure 15 displays very little change between 2008 and 2030 in the T2 aquifer over most of the modelled area.

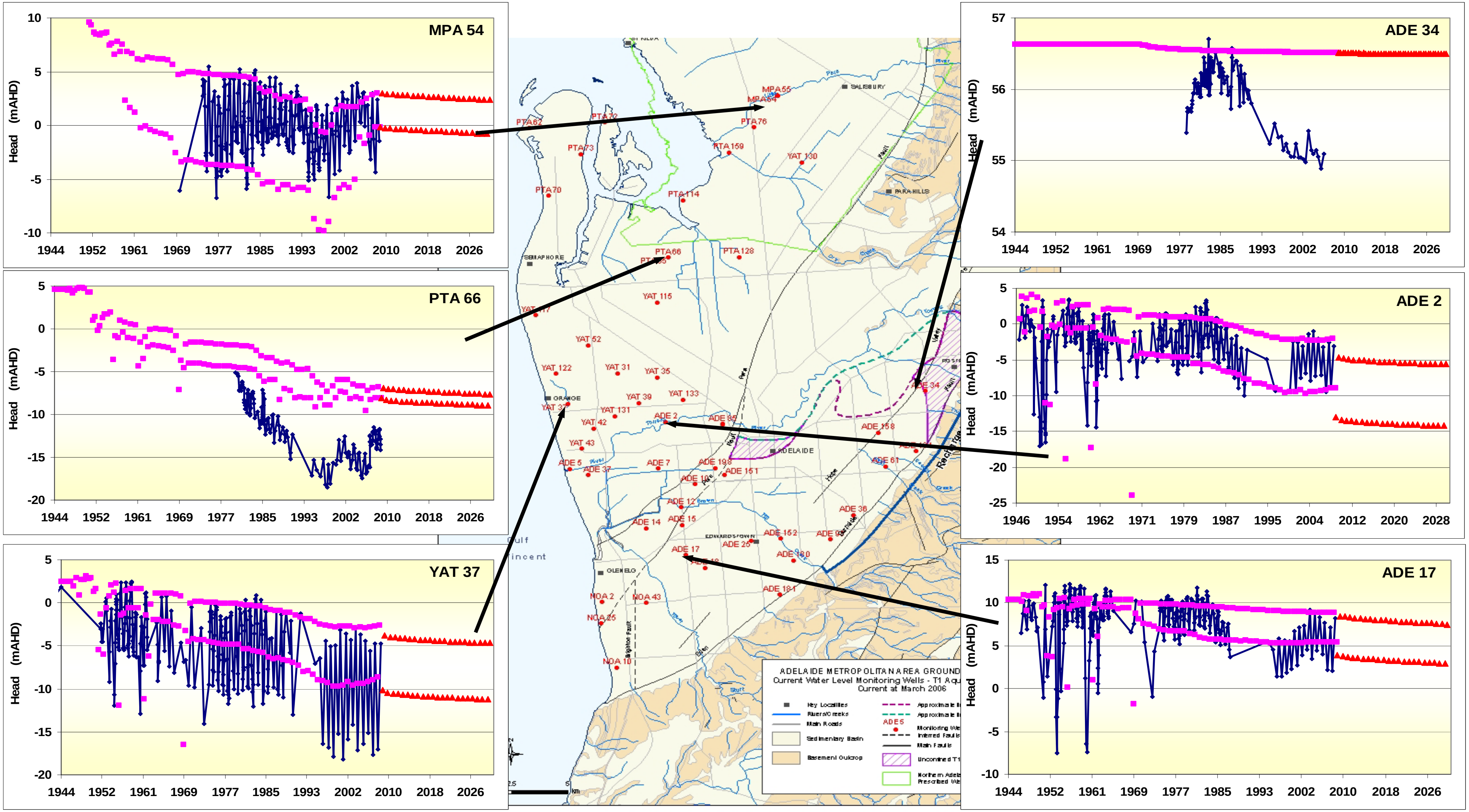


Figure 12. T1 aquifer transient calibration and prediction results

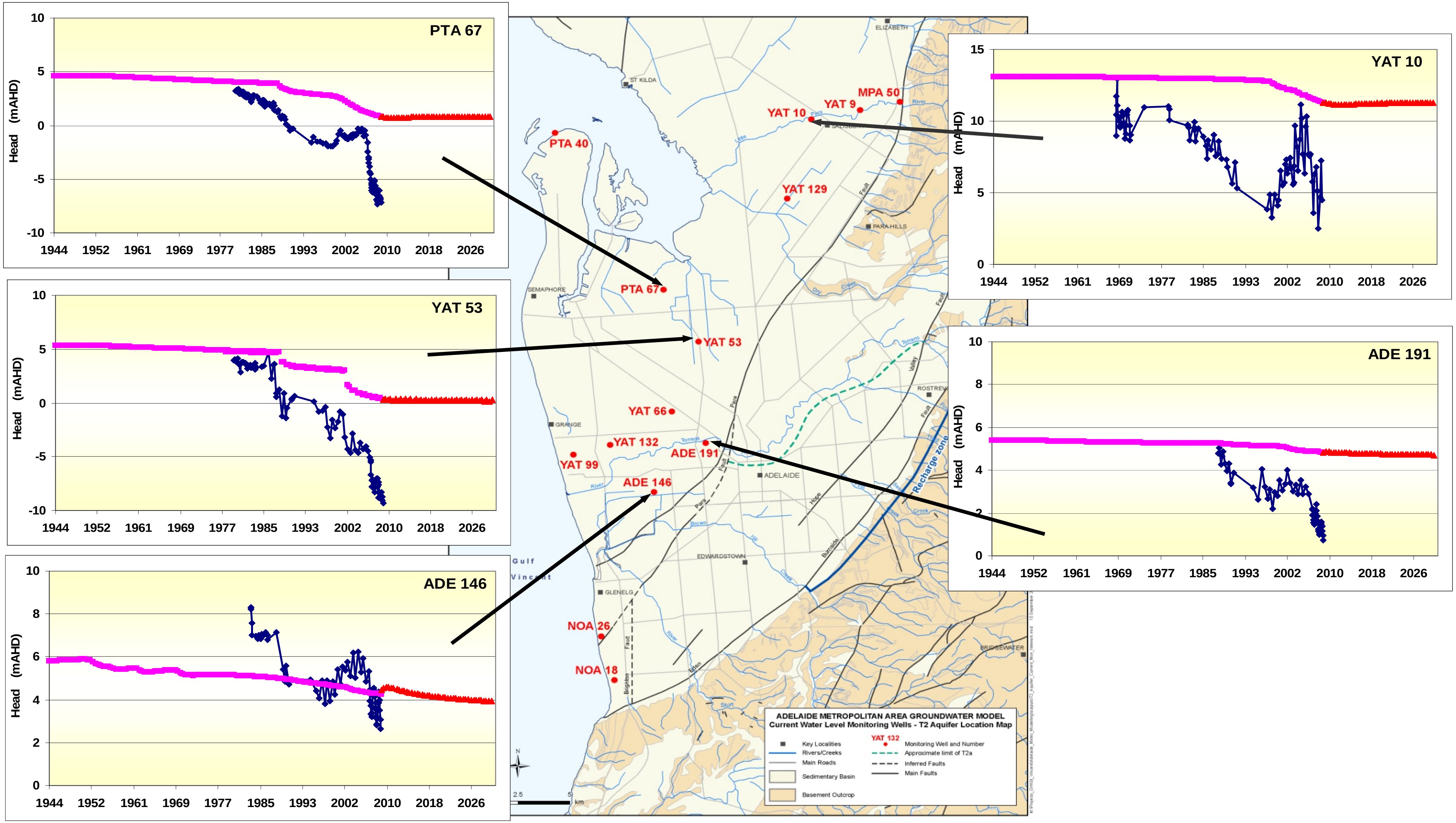


Figure 13. T2 aquifer transient calibration and prediction results

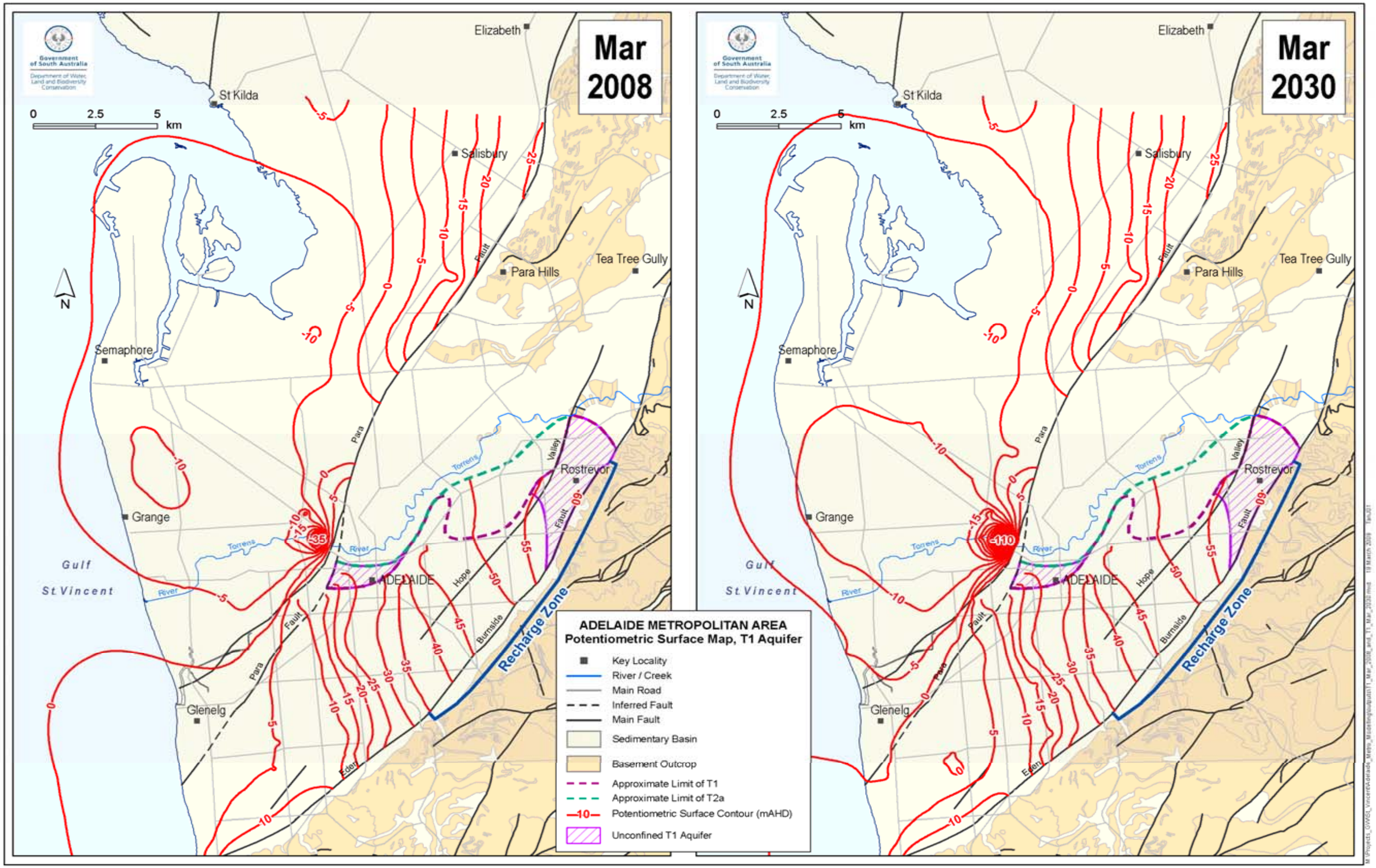


Figure 14. **T1 aquifer March potentiometric surface map –2008 and 2030**

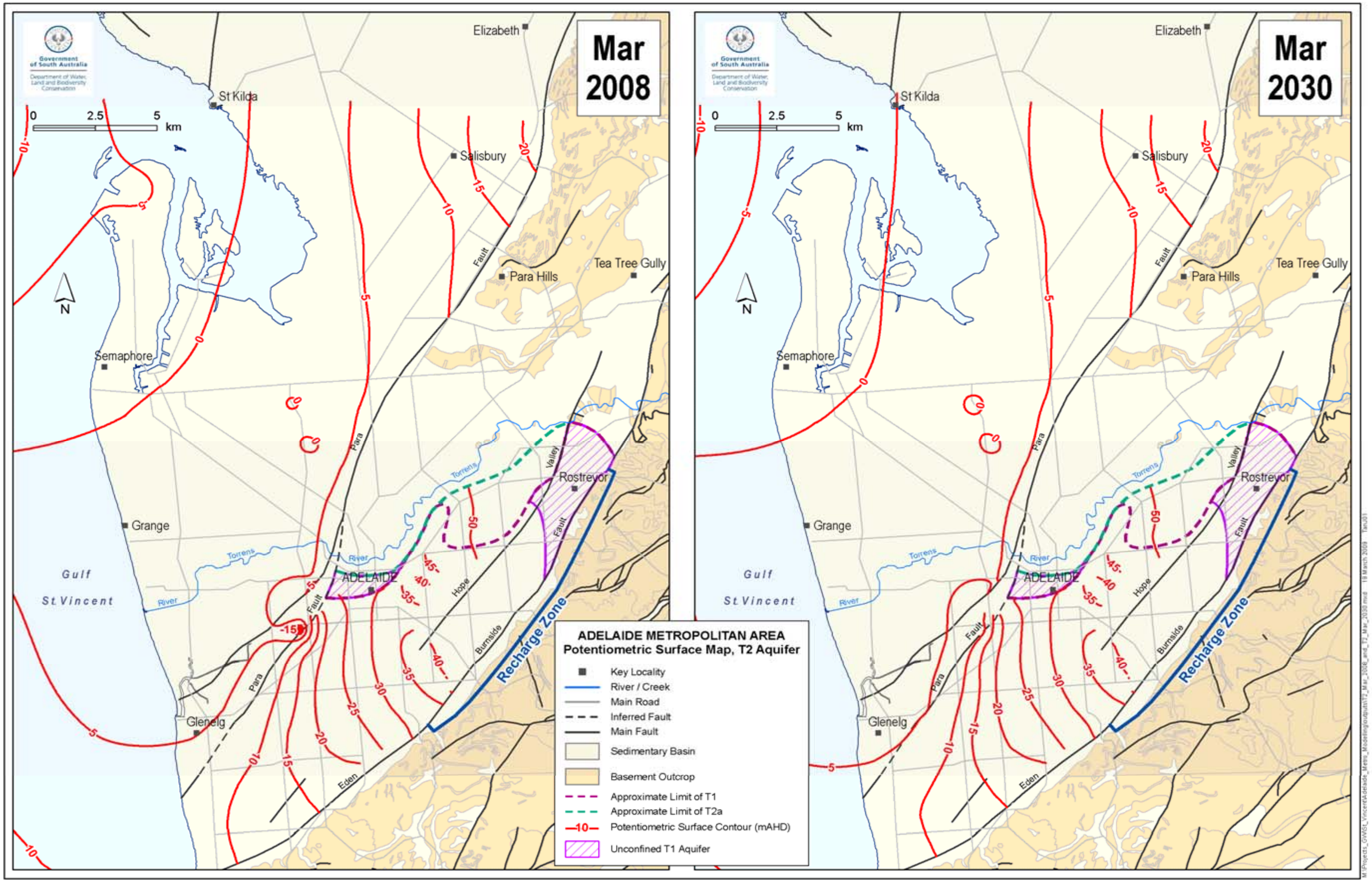


Figure 15. T2 aquifer March potentiometric surface map –2008 and 2030

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	g	10^{-6} g	mass
microlitre	L	10^{-9} m^3	volume
milligram	mg	10^{-3} g	mass
millilitre	mL	10^{-6} m^3	volume
millimetre	mm	10^{-3} m	length
minute	min	60 s	time interval
second	s	base unit	time interval
tonne	t	1000 kg	mass
year	y	365 or 366 days	time interval

~	approximately equal to
D	hydrogen isotope composition
^{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

Act (the) — In this document, refers to the *Natural Resources Management Act* (SA) *2004*.

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

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

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

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.

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

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

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

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

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

Groundwater — *See underground water.*

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

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

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

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

MLR — Mount Lofty Ranges.

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.)*

Obswell — Observation Well Network.

Permeability — A measure of the ease with which water flows through an aquifer or aquitard. The unit is m^2/d.

Potable water — Water suitable for human consumption.

Potentiometric head — The potentiometric head or surface is the level to which water rises in a well due to water pressure in the aquifer; the unit is metres (m).

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.)*

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

SA Water — South Australian Water Corporation (Government of South Australia).

Specific storage (S_s) — Specific storativity. The amount of stored water realised from a unit volume of aquifer per unit decline in head. It is dimensionless.

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

(S) — Storativity**.** Storage coefficient. The volume of groundwater released or taken into storage per unit plan area of aquifer per unit change of head. It is dimensionless.

TDS —Total Dissolved Solids; the unit is milligrams per litre (mg/L).

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

T — Transmissivity**.** A parameter indicating the ease of groundwater flow through a metre width of aquifer section (taken perpendicular to the direction of flow); the unit is m^2/d.

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

USGS — United States Geological Survey.

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.

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