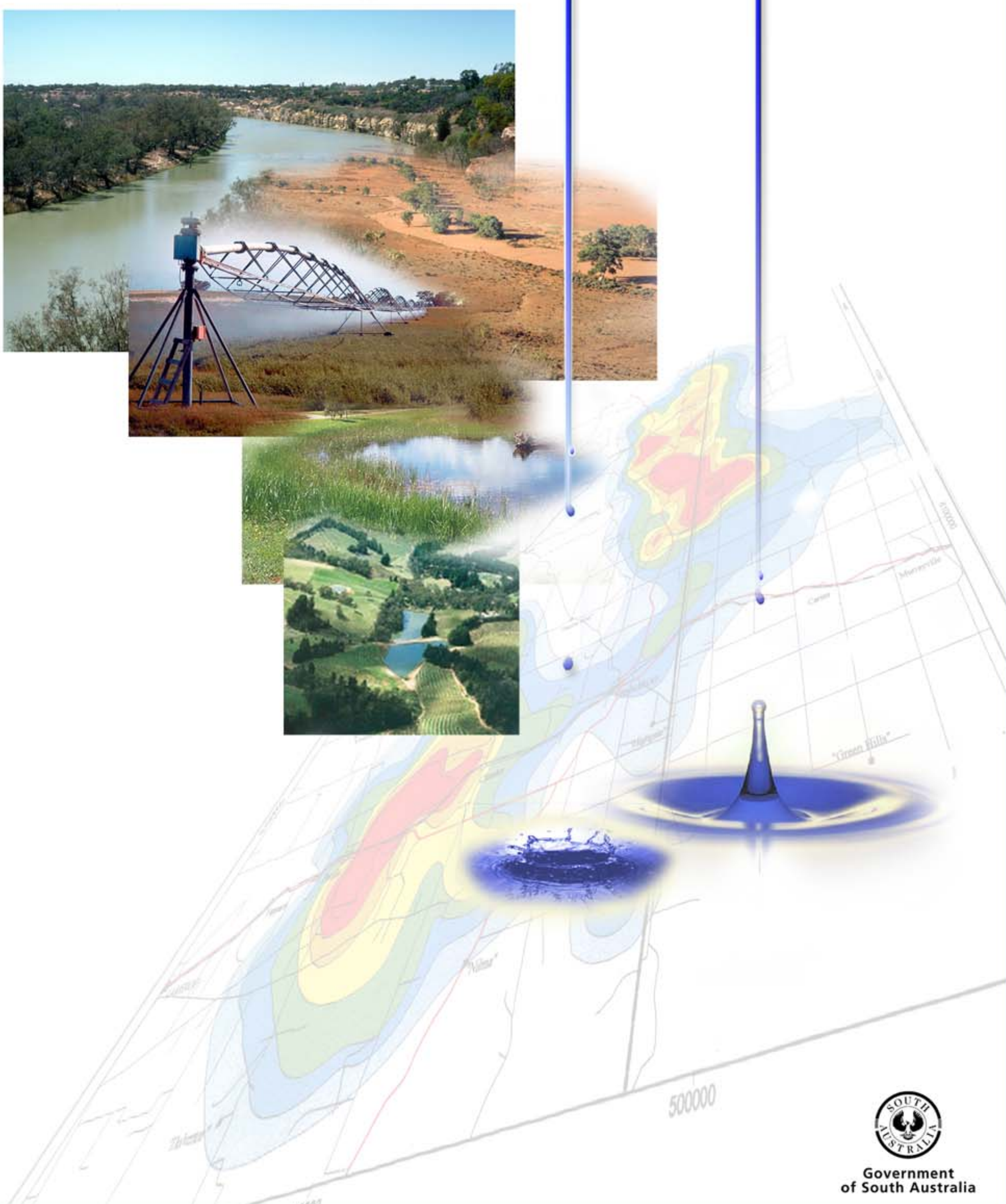
Department for
Water Resources

Northern Adelaide Plains groundwater review

Report DWR 2001/013



Government
of South Australia

Northern Adelaide Plains groundwater review

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September 2001

DWR Report 2001/013

Department for Water Resources

Government of South Australia

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NOTE
This report uses hydrogeological information from up to 1999.

FOREWORD

South Australia's water resources are fundamental to the economic and social wellbeing of the State. Water resources are an integral part of our natural resources. In pristine or undeveloped situations, the condition of water resources reflects the equilibrium between rainfall, vegetation and other physical parameters. Development of surface and groundwater resources changes the natural balance and causes degradation. If degradation is small, and the resource retains its utility, the community may assess these changes as being acceptable. However, significant stress will impact on the ability of a resource to continue to meet the needs of users and the environment. Degradation may also be very gradual and take some years to become apparent, imparting a false sense of security.

Management of water resources requires a sound understanding of key factors such as physical extent (quantity), quality, availability, and constraints to development. The role of the Resource Assessment Division of the Department for Water Resources is to maintain an effective knowledge base on the State's water resources, including environmental and other factors likely to influence sustainable use and development, and to provide timely and relevant management advice.

Bryan Harris
Director, Resource Assessment Division
Department for Water Resources

ABBREVIATIONS

General

AHD	Australian height datum
ASR	Aquifer storage and recovery
Cb1–Cb7	Quaternary confining beds of the Northern Adelaide Plains; Cb1 being shallowest
MFP	Multi Function Polis
NAP	Northern Adelaide Plains
P	Precambrian fractured rock aquifer of the Northern Adelaide Plains
ppb	parts per billion
Q1–Q6	Quaternary aquifers of the Northern Adelaide Plains; Q1 being shallowest
T1–T4	Tertiary aquifers of the Northern Adelaide Plains; T1 being shallowest
yr	year
Δs	calculated change in storage

Measurement

Units of measurement used in this volume are those of the International System of Units (SI) as well as units outside the SI which have been authorised for use within Australia's metric system.

d	day (time interval; 86.4 x 10^3 s)
ha	hectares (area 10^4 m^2)
h	hour (time interval; 3.6 x 10^3 s)
kg	kilogram (mass)
km^2	square kilometre
L	litre (volume; 10^{-3} m^3)
L/s	litres per second
m	metre (length)
m/d	metres per day
m^2/d	square metres per day
mg	milligram (10^{-6} kg)
mg/L	milligrams per litre
min	minute (time interval; 60 s)
ML	megalitre (10^6 L)
ML/yr	megalitres per year

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Report DWR 2001/013

Department for Water Resources South Australia
Groundwater Assessment Division
November 1998

Northern Adelaide Plains groundwater review

Dr Nabil Z. Gerges

ABSTRACT

The availability of good quality groundwater from two confined Tertiary aquifers (T1 and T2) under the Northern Adelaide Plains has encouraged the development of 3000 ha of horticulture in the area since the 1950s. At present, approximately 3500 ML is extracted annually from aquifer T1 and between 13 500 and 14 000 ML from aquifer T2.

Before the 1950s, water levels of both aquifers were approximately 10 m above ground level.

Most extraction in the southern part of the Northern Adelaide Plains occurs from aquifer T1, and has resulted in the formation of cones of depression in the Waterloo Corner irrigation area and the Penrice Soda industrial area.

In the northern parts of the area, extraction from aquifer T2 is concentrated in a relatively small area, where salinity is below 1500 mg/L and aquifer transmissivity is relatively low. Consequently, a depletion of elastic storage and the development of a pronounced cone of depression (up to 75 m decline in water level in the centre of the cone) is occurring during summer. This cone of depression does not recover completely in winter.

The cone of the depression is a result of the inability of the aquifer to transmit water into its centre, where a high concentration of pumping wells operate extracting large volumes of groundwater.

It is evident that over approximately 50 years of heavy extraction, the area has suffered a massive reduction in pressure and, therefore, water levels have declined steeply in the middle of the cone of depression.

Currently during summer, the cone of depression in the T2 aquifer reaches the top of the aquifer (unconfined situation) in the Virginia area. As pumping continues, it is expected that a minor decline in water levels will continue to occur in the centre of the area (Virginia area) and a major decline will continue outside the centre of the cone. As the cone progressively expands, the unconfined situation will spread laterally, covering a large portion of the irrigated area.

Declining water levels have resulted in reduced well yields and increased pumping costs.

Salinity in some wells has increased significantly primarily due to leakage via old and poorly constructed wells. In others, it is possibly caused by lateral flow from the surrounding saline aquifer margins.

The prime source of recharge to the Tertiary aquifers is from the rainfall-fed fractured rock bedrock aquifers in the Adelaide Hills. The higher elevation of water levels in the Hills acts as a source of pressurised water to the less elevated Tertiary aquifers. The conceptual model of the area indicates that lateral flow occurs via preferential paths through the fractured rock aquifer into the Tertiary aquifers.

Several solutions to combat the decline in water level and the salinity increases have been proposed, including; eliminating winter extraction, implementing aquifer storage and recovery technology in the area during winter months (particularly in the centre of the cone), and using other sources such as surplus mains water and/or treated reclaimed water from Bolivar.

It is anticipated that the usage of treated effluent water delivered by the Bolivar pipeline, particularly during the winter months, will reduce the irrigator's reliance on groundwater. A greater use of effluent water which results in a corresponding reduction in groundwater extraction and implementation of aquifer storage and recovery technology will be effective approaches in improving the condition of the basin.

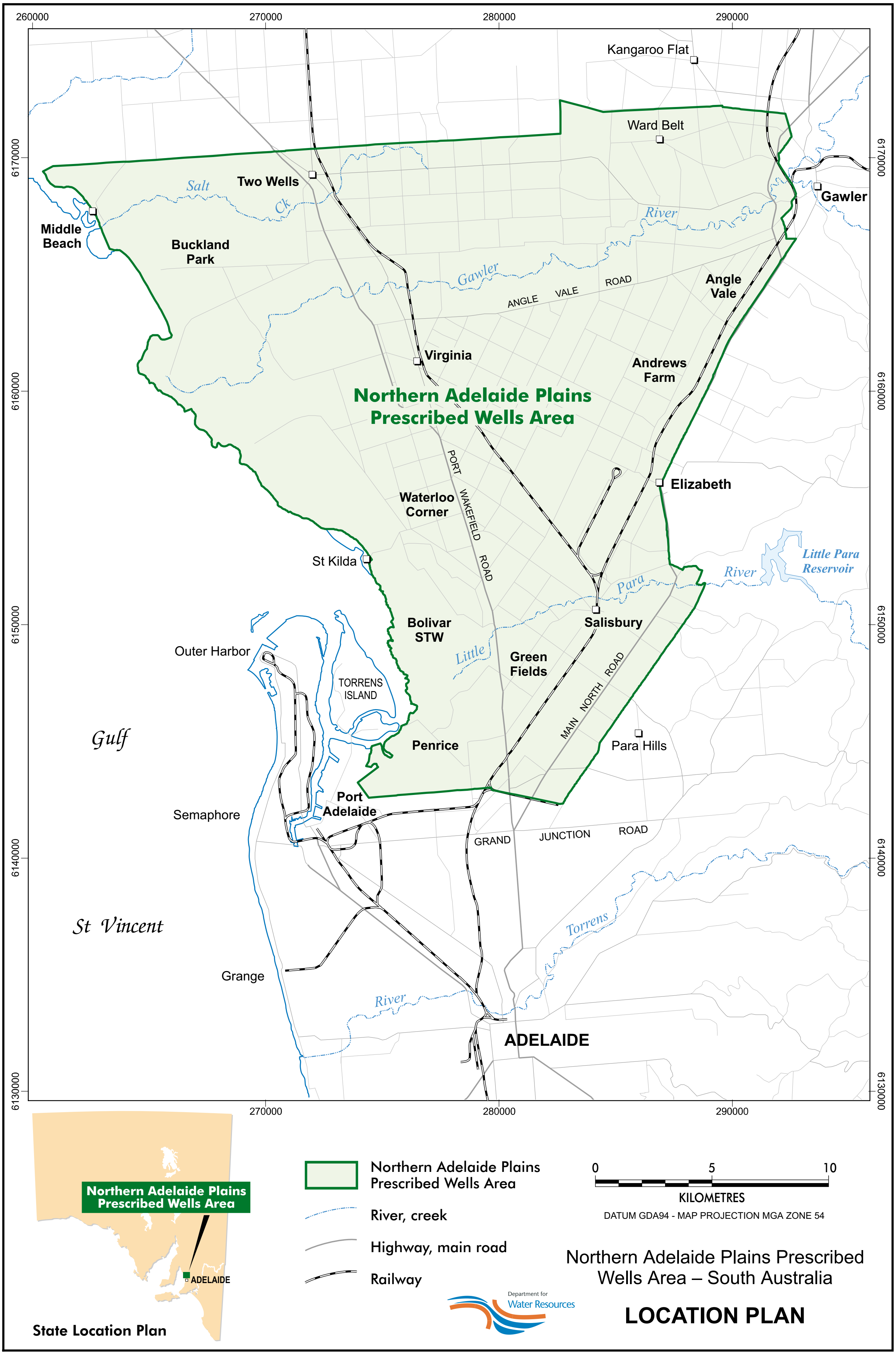
Several modelling scenarios to enable the selection of the most appropriate management option are to be examined.

1.0 INTRODUCTION

The Northern Adelaide Plains (NAP) occupies about 750 km^2 of the Adelaide coastal plain. It is hydraulically connected to the Adelaide Metropolitan area and forms part of the Adelaide Plains sub-basin, which in turn is part of the St Vincent Basin (Fig. 1). The Plains are formed by Tertiary and Quaternary sediments up to 600 m thick. These contain up to 10 aquifer systems overlying a Precambrian fractured rock aquifer.

Several ephemeral watercourses, including the Gawler and Little Para Rivers, drain westerly toward St Vincent Gulf. In addition, several small creeks rise in the Adelaide Hills and drain westerly into the plain.

There are numerous aquifers in the area (Figs 2–2b). The Quaternary sediments contain up to six thin aquifers but most areas consist of four. The Tertiary sediments contain up to four aquifers designated first, second, third and fourth in, order of increasing depth. Groundwater of varying quality occurs in both the Quaternary and Tertiary aquifers.



Northern Adelaide Plains Prescribed Wells Area – South Australia

LOCATION PLAN

GeoTech Graphics 384-1684

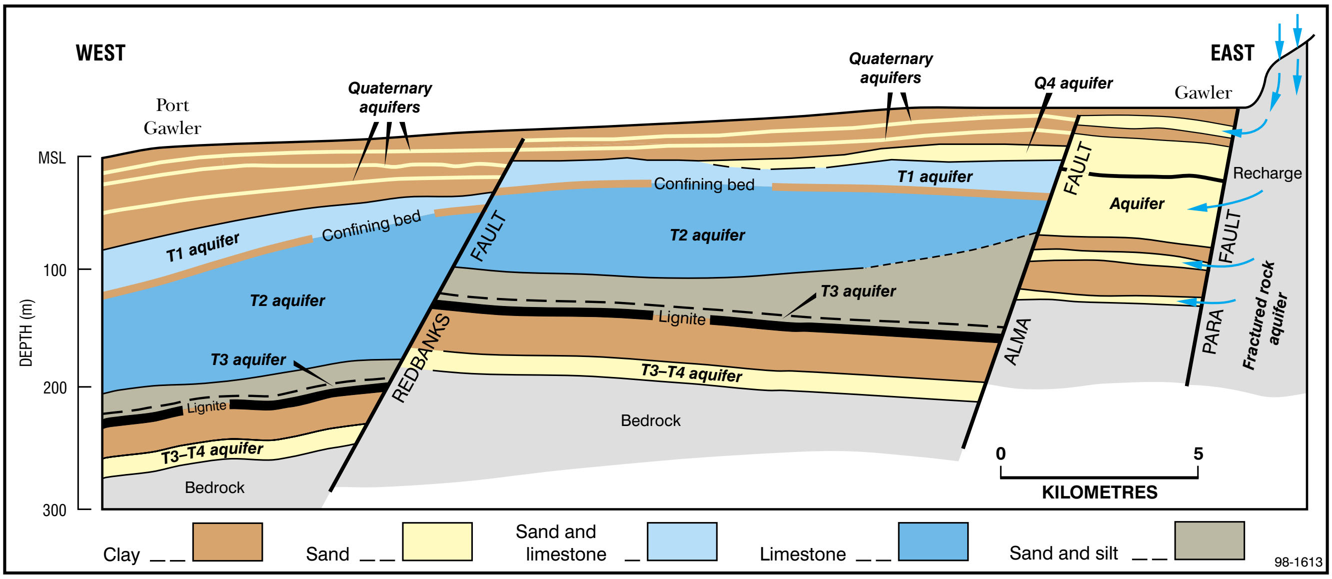


Figure 2 NAP diagrammatic east–west cross-section along Gawler River showing aquifers and confining layers

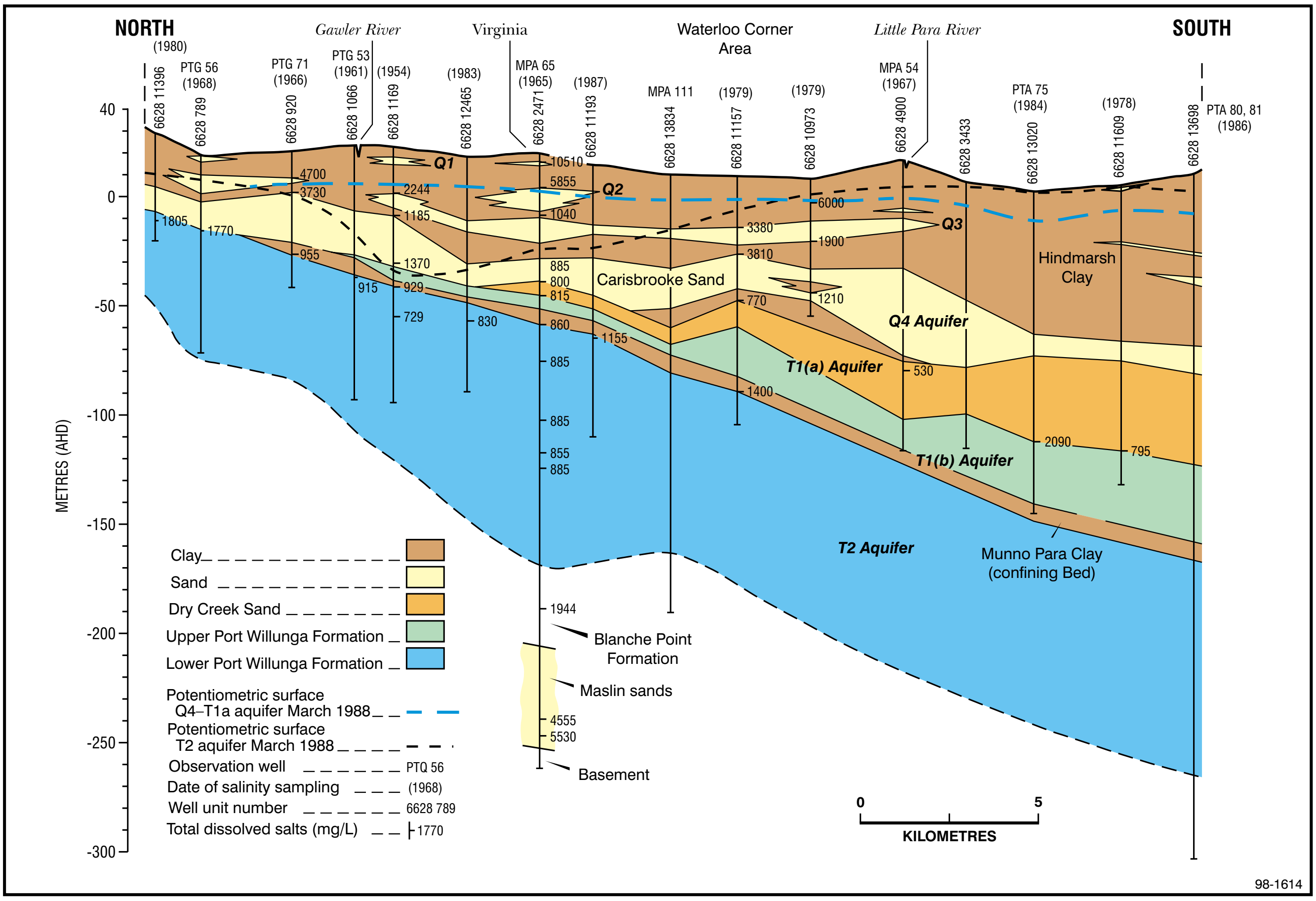


Figure 2a NAP diagrammatic north–south cross-section

At present, the majority of the extraction of approximately 17 500–18 500 ML/yr occurs from some 1200 wells completed in the first and the second Tertiary aquifers and, to a much lesser extent, in the Quaternary aquifers. Most of the water is used for horticultural and industrial purposes.

The bulk of abstracted groundwater in the NAP is obtained from the top of Tertiary aquifers designated first (T1) and second (T2) in order of increasing depth. At present, extraction of 17 500 ML/yr occurs from approximately 1200 wells completed mainly in the first and second Tertiary aquifers and also in the Quaternary aquifers, with most of the water being used for industrial and horticultural purposes.

Extractions from the T1 and T2 aquifers has been constant for the past decade. Total extractions from the T2 aquifer, calculated at 13 500 ML/yr, occurs mostly in Virginia and Angle Vale areas. Extractions from the T1 aquifer in the proclaimed region occur mainly from three pumping areas:

- Waterloo Corner area — with an approximate total extraction of 1225 ML/yr.
- Little Para River area — with an approximate total extraction of 525 ML/yr.
- The Penrice Soda Industrial area — with an approximate total extraction of 1354 ML/yr (inside the NAP proclaimed region).*

In addition, an estimated 500 ML/yr is extracted from Quaternary aquifers over the NAP area. Outside the NAP area, and in the Adelaide Metropolitan area, groundwater is used mainly from the T1 aquifer. Extractions average 5000 ML/yr and the water is used for both irrigation and industrial purposes.

The problem of contamination of good quality water by saline water from overlying aquifers has been recognised. This is mainly due to incorrect drilling and completion methods and corroded casing where the wells now act as a connection between the T1 aquifer and overlying saline aquifers. Over-pumping of the Tertiary aquifer, may have induced downward leakage from the overlying saline aquifer through a leaky confining layer and lateral ingress in some area.

This report concentrates on the historic recharge mechanisms and reviews the present status of the basin.

2.0 WATER ALLOCATIONS AND WATER USAGE

The current total licensed water allocation within the NAP is 26 500 ML/yr. Average use over the last 10 years has been between 17 000–18 000 ML/yr, with use in dry years as high as 24 000 ML.

At present, extraction of 17 500 ML/yr (Figs 3 and 4) occurs from approximately 1200 wells (Fig. 5) completed in both the first and the second Tertiary aquifer. Most of the water is used for industrial and horticultural purposes. Average monthly usage of water from the T1 and T2 aquifers within the NAP is shown in Figure 3. Figure 4 illustrates the total average monthly groundwater use for all aquifers on the NAP. The volume of groundwater identified as unaccounted on Figures 3 and 4 represents the difference between allocated volume and metered use.

* The annual inside and outside-prescribed area of NAP is estimated to range between 2500 and 2700 ML/yr.

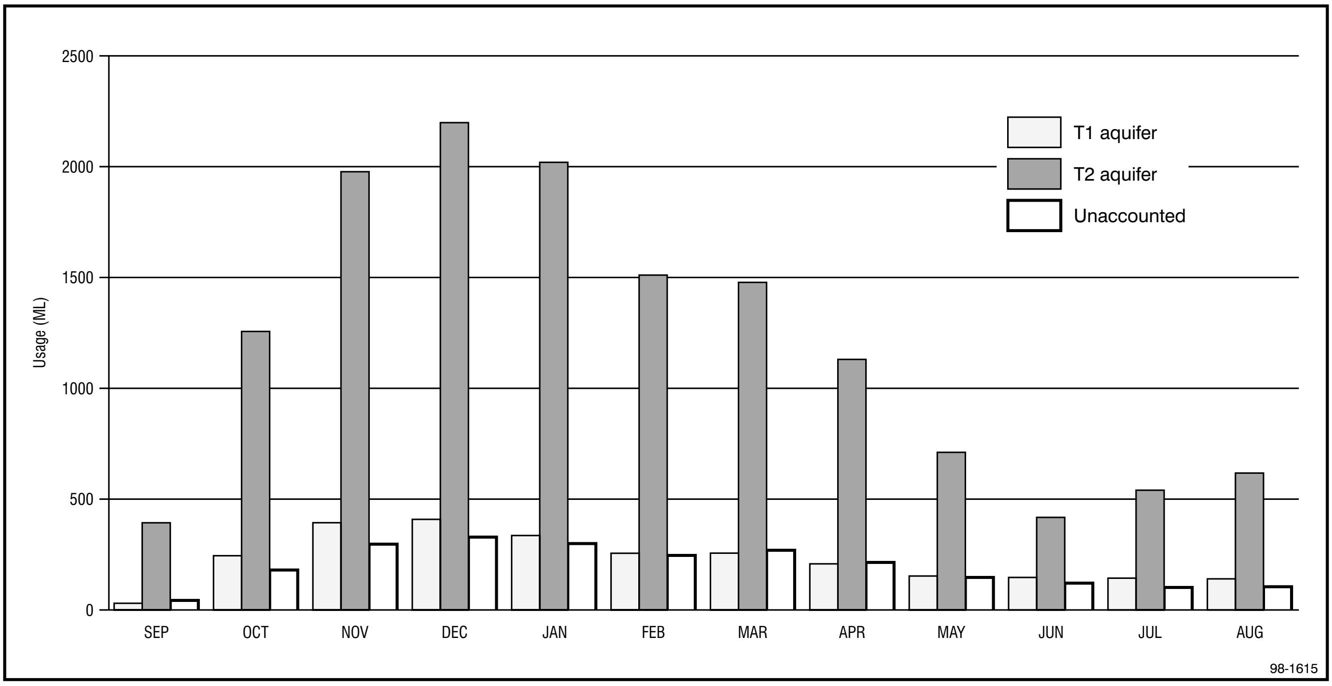


Figure 3 Average monthly water usage T1 and T2 aquifer, by month, NAP

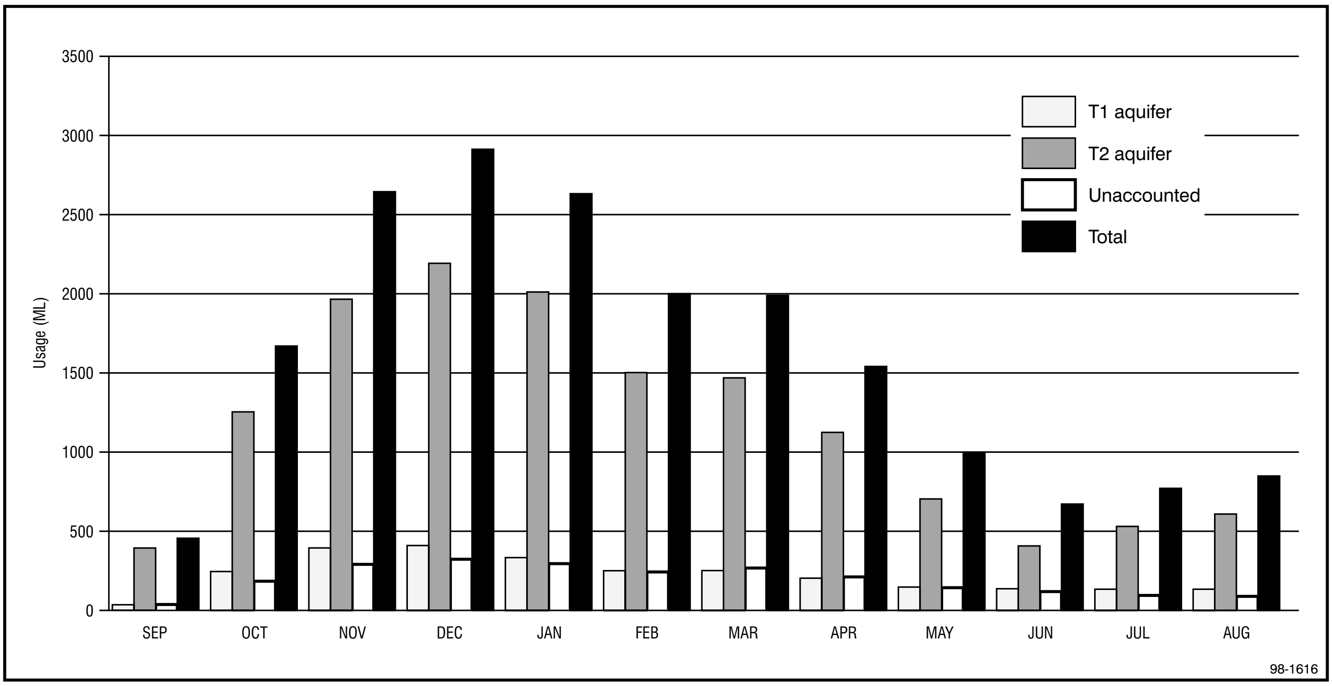


Figure 4 Total average monthly water usage NAP

Total extractions from the T2 aquifer are approximately 13 500 ML/yr, and occurs mostly in the vicinity of Virginia–Angle Vale area. Summer usage from this aquifer is calculated at approximately 10 000 ML while winter usage from T2 aquifer is between 3000–3500 ML.

Extractions from the T1 aquifer are between 3500–4000 ML from three main pumping areas:

- The Waterloo Corner area, with an approximate total extraction of 1225 ML/yr
- The Little Para River area, with an approximate total extraction of 525 ML/yr
- The Penrice Soda Industrial area, where approximate total extractions range between 2500 and 2700 ML (including extractions outside the NAP Prescribed Area).

Extraction from Quaternary aquifers over the NAP Prescribed Area and other unspecified aquifers has been calculated at approximately 400 ML/yr. Total extraction from groundwater for 1998–99 was calculated at 18 973 ML and usage from each aquifer is shown in Table 1.

Table 1 Extraction from various aquifers during 1998–99

	Aquifer						
	AQ	**Q1**	**Q2**	**Q3**	**Q4**	**T1**	**T2**
Extraction (ML)	0	2	40	125	314	3901	14690
Allocation (ML)	4.31	48	216	351	351	25616	

Outside the NAP, and within the Adelaide Metropolitan area, an additional 5000 ML/yr of groundwater is used on average. This is mainly from the T1 aquifer for irrigation and industrial purposes.

3.0 GROUNDWATER RESOURCE MONITORING

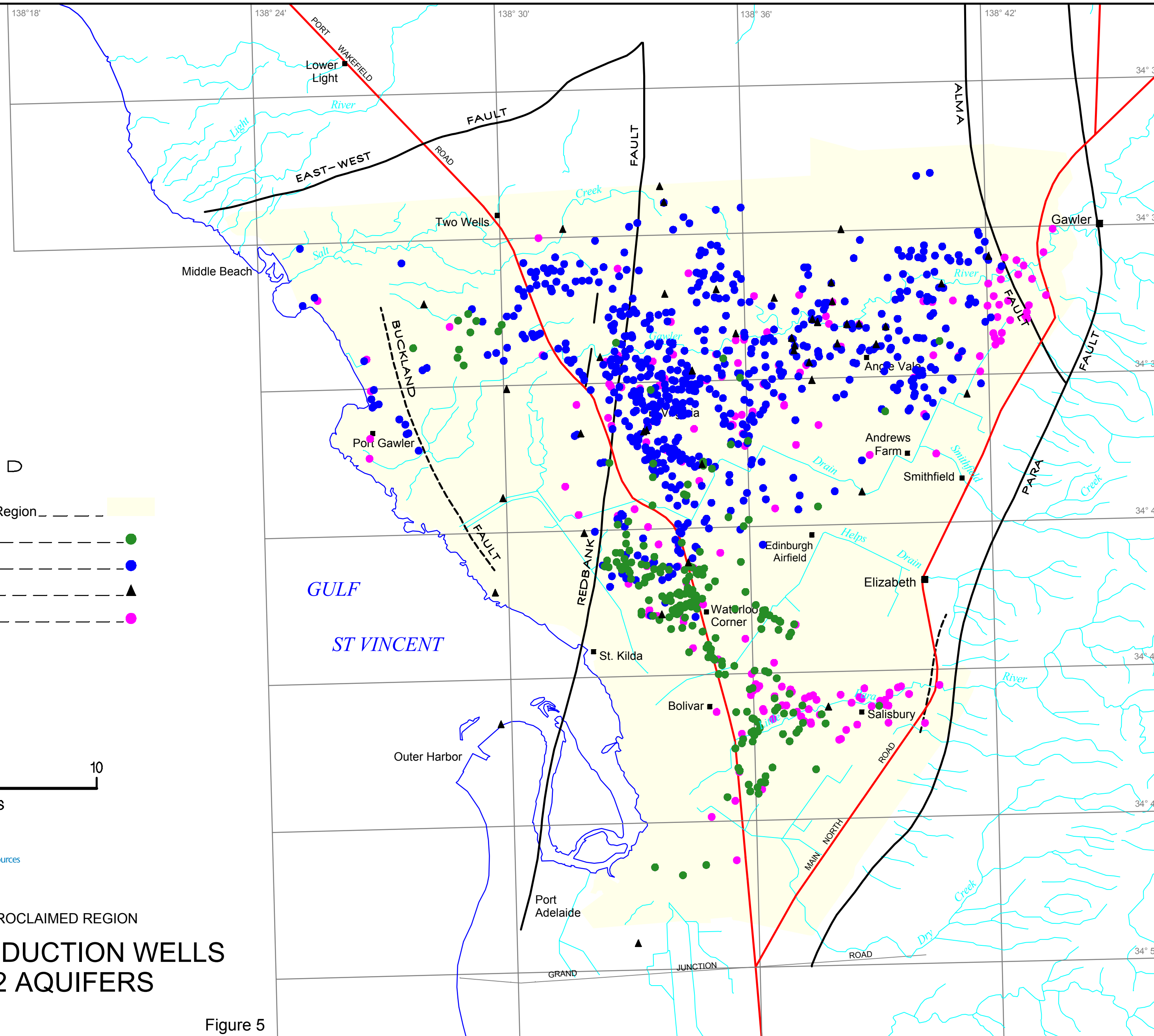
3.1 WATER LEVEL MONITORING

A network of Quaternary and Tertiary observation wells (Figs 6–8) has been established since the 1960s to examine the potentiometric surface of the NAP and to monitor water level trends in the area.

The existing NAP monitoring network consists of 90 wells. In addition, 52 wells (33 Quaternary wells and 19 Tertiary wells) are currently not monitored. Twenty of these are privately owned and are essentially inaccessible, however the status of the remaining 32 wells is under investigation.

Within the existing monitoring wells, 30 monitor the Quaternary aquifers, and 60 monitor the Tertiary aquifers.

The Tertiary network consists of 19 ‘T1 wells’, 35 ‘T2 wells’ and five ‘T3 wells’. One observation well (MPA 140) is east of the Alma fault, and was completed in undifferentiated Tertiary sediments. Three wells lack completion details, but based on drilling depths have been identified as T1 aquifer wells.



LEGEND

Northern Adelaide Plains Proclaimed Region

T1 aquifer production well

T2 aquifer production well

T2 aquifer observation well

Other production well

0 5 10

KILOMETRES

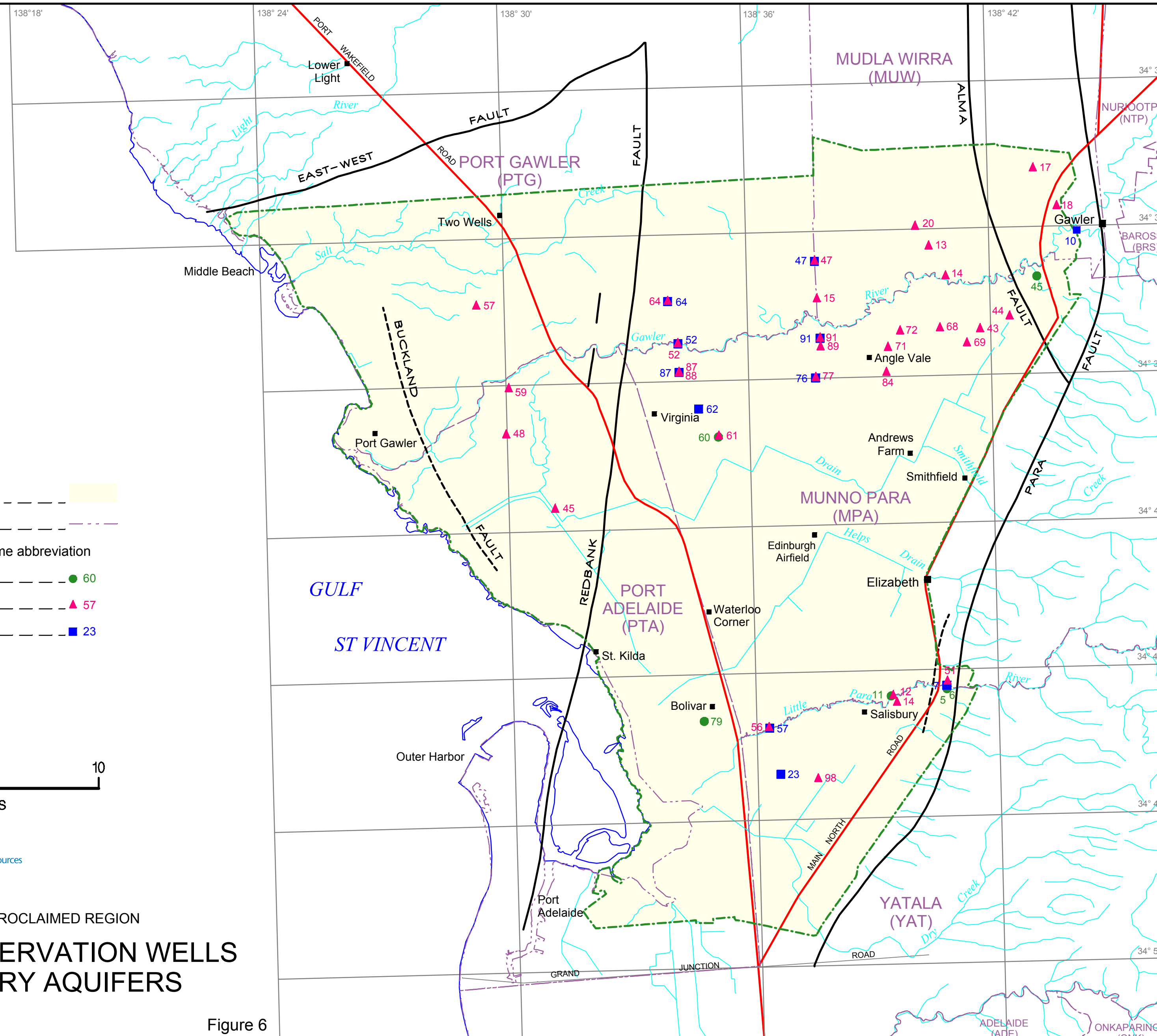
Department for Water Resources

NORTHERN ADELAIDE PLAINS PROCLAIMED REGION

DISTRIBUTION OF PRODUCTION WELLS IN THE T1 AND T2 AQUIFERS

Figure 5

QD7 101446NG: 101446.DTA 98-1617



LEGEND

Northern Adelaide Plains Proclaimed Region

Hundred boundary

Observation number prefixed by hundred name abbreviation

Q1 aquifer observation well and number — 60

Q3 aquifer observation well and number — 57

Q4 aquifer observation well and number — 23

0 5 10

KILOMETRES

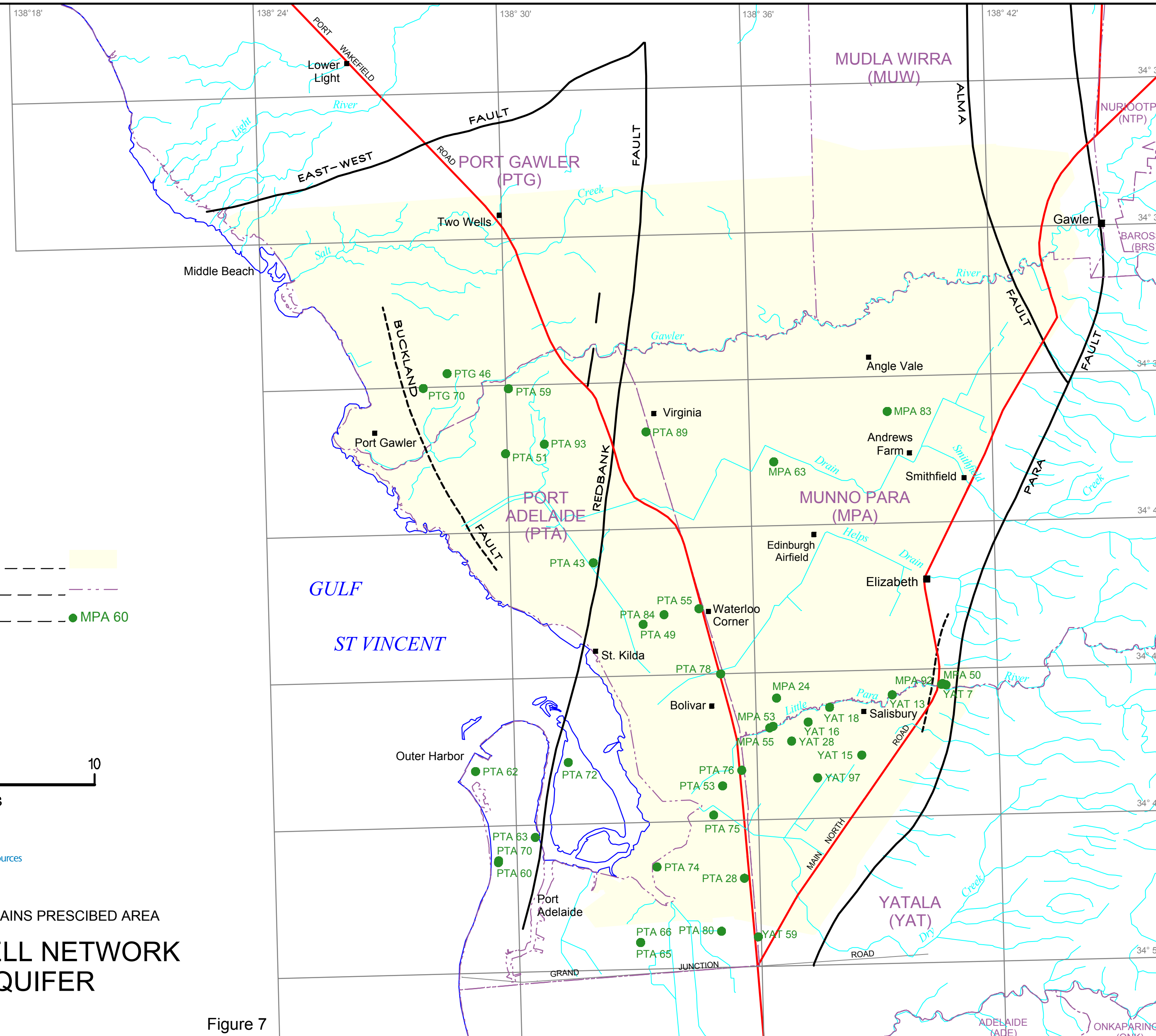
Department for Water Resources

NORTHERN ADELAIDE PLAINS PROCLAIMED REGION

DISTRIBUTION OF OBSERVATION WELLS IN THE QUATERNARY AQUIFERS

Figure 6

QD7 101446NG: 101446.DTA 98-1618



LEGEND

Northern Adelaide Plains Proclaimed Region

Hundred boundary

Observation well and number — MPA 60

0 5 10

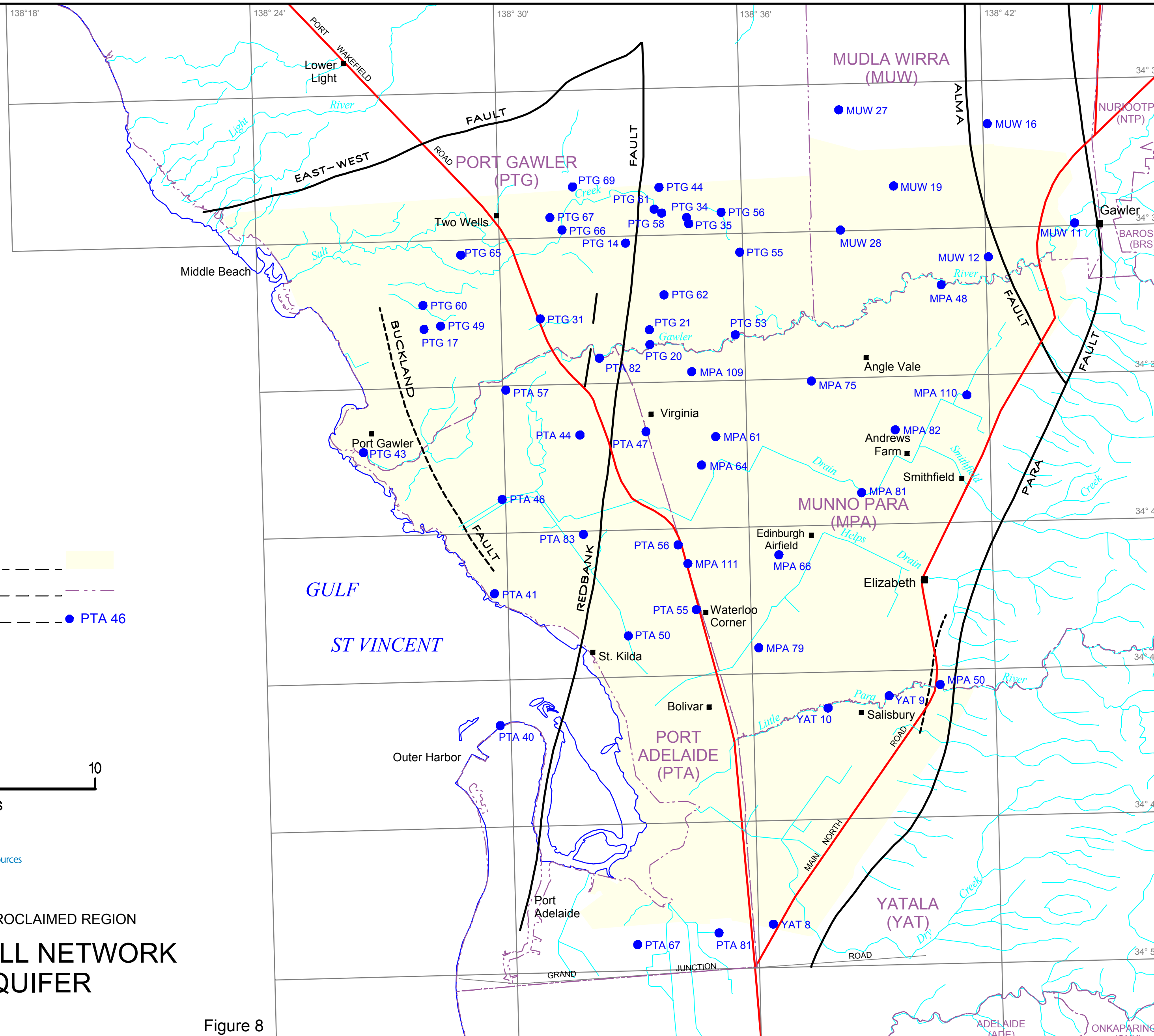
KILOMETRES

NORTHERN ADELAIDE PLAINS PRESCIBED AREA

OBSERVATION WELL NETWORK IN THE T1 AQUIFER

Figure 7

QD7 101446NG: 101446.DTA 98-1619



LEGEND

Northern Adelaide Plains Proclaimed Region

Hundred boundary

Observation well and number — PTA 46

0 5 10

KILOMETRES

Department for Water Resources

NORTHERN ADELAIDE PLAINS PROCLAIMED REGION

OBSERVATION WELL NETWORK IN THE T2 AQUIFER

Figure 8

QD7 101446NG: 101446.DTA 98-1620

3.2 SALINITY MONITORING

Ten-year salinity data from the Department for Water Resources on a set of 220 licensed production wells has been retrieved and examined for salinity trends. The production wells are considered representative of different areas and aquifers in the NAP area. This set was subsequently reduced to 199, since two wells were duplicated in the original list, 18 were completed in Quaternary aquifers and one was completed in a Precambrian fractured rock aquifer. The set includes 37 ‘T1 wells’ and 162 ‘T2 wells' (Schuster and Gerges, 1999). Figures 9 and 10 show the location of sampled wells. At present, all water licence owners are required to submit an annual water sample from equipped production wells.

4.0 HYDROGEOLOGY

There are numerous aquifers in the area (Figs 2 and 2a), with the Quaternary sediments containing mostly four, but up to six, thin aquifers, and the Tertiary sediments containing up to four aquifers. Groundwater of varying quality occurs in these aquifers. Precambrian rocks form useful fractured rock aquifers with generally good quality water at shallow depth.

Both the Quaternary and Tertiary aquifers were designated identifiers in order of increasing depth. The Quaternary aquifers were numbered ‘Q1’ to ‘Q6’, the Tertiary aquifers ‘T1’ to ‘T4’, and the Precambrian fractured rock aquifer was identified as ‘P’.

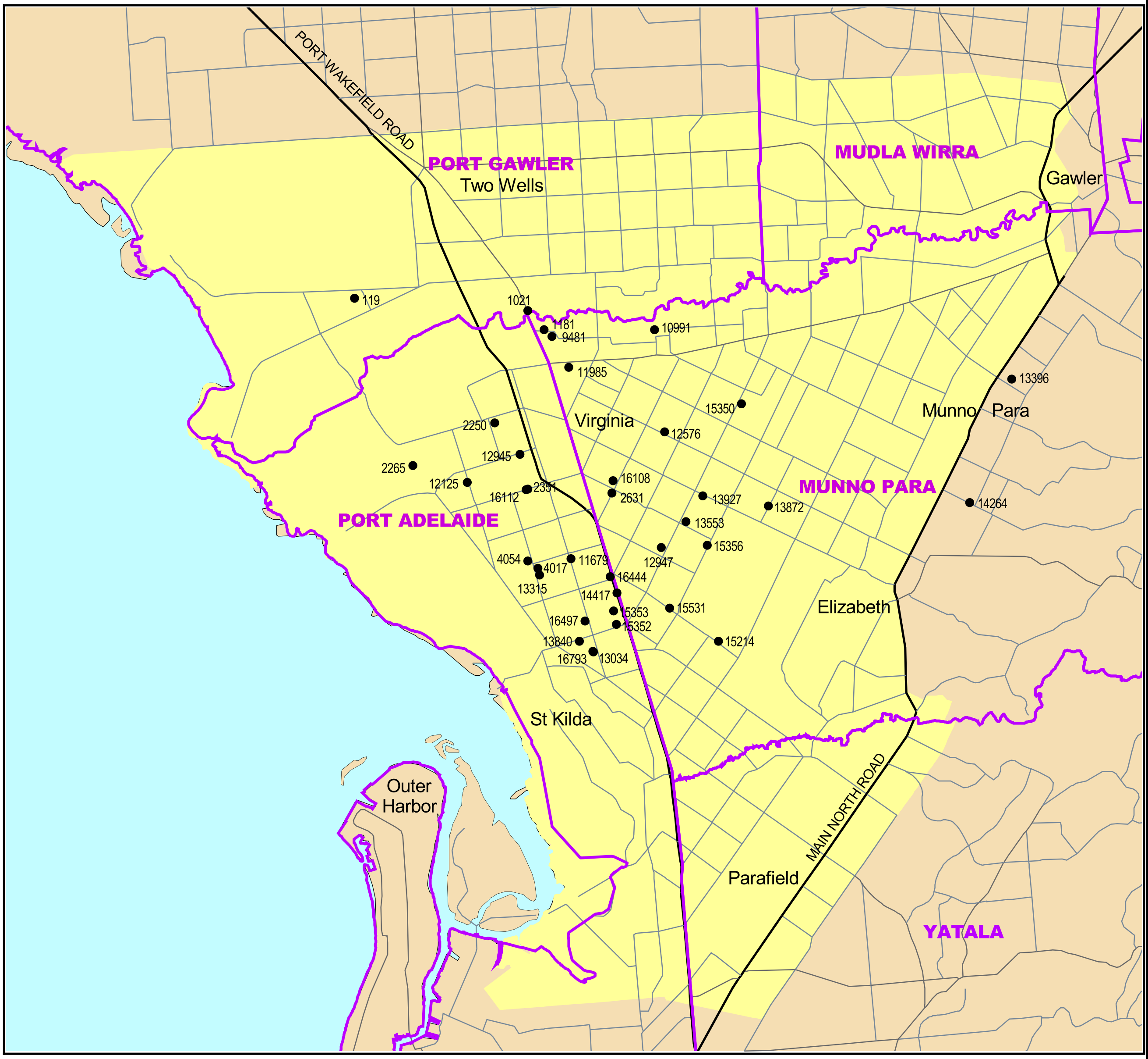
4.1 QUATERNARY AQUIFER SYSTEM

The main lithology of the Quaternary sediments is mottled clay and silt with interbedded sand, gravel and thin sandstone. The sands, gravels and sandstones represent aquifers and up to four Quaternary aquifers can be recognised over most of the region from drill log and geophysical log interpretation. In the southern area, five or six Quaternary aquifers have been recognised. These are designated Q1 to Q6 in order of increasing depth. These aquifers vary greatly in thickness (from 1–60 m), lithology and hydraulic conductivity.

The uppermost Quaternary aquifers (Q1–Q3) comprise mainly clay and silt with thin layers of sand. These form minor unconfined to mainly confined systems. Salinities are high in the upper sands of Q1 and Q2 and vary from 2000 to 15 000 mg/L towards the coast. Salinity decreases with depth to between 1500 to 3000 mg/L in the Q3 system. The sandy aquifers are at their shallowest near the Gawler and Little Para Rivers and salinities are generally lower (400–1500 mg/L) due to winter recharge from the rivers. The Quaternary aquifers are not usually used for commercial irrigation because of their low yield.

Gerges (1987) showed that the southern area (Penrice Soda) is a terminus for groundwater flow in Quaternary aquifers beneath the western suburbs of Adelaide. This is confirmed by the high salinity of groundwater, which indicates that evaporation from the shallow groundwater is concentrating salt within the area . At some sites, shallow Quaternary aquifer salinities could be up to three times the salinity of seawater.

Below the shallow Quaternary aquifers, the Hindmarsh Clay generally forms a confining layer to the underlying main aquifer systems. The lower Quaternary aquifer is called the Carisbrooke Sands Aquifer (Q4), and forms a continuous layer over

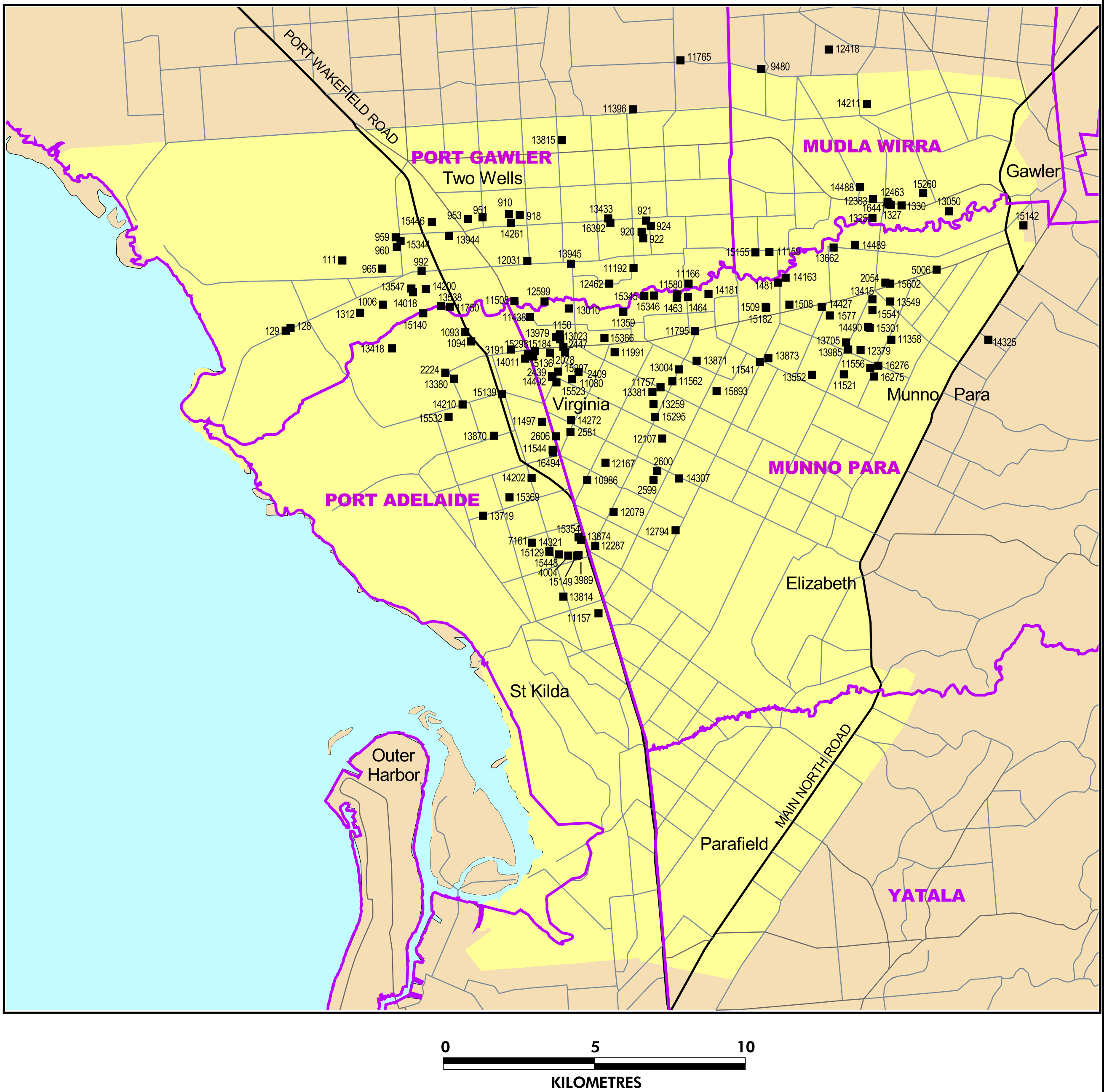


Northern Adelaide Plains - Groundwater Salinity Survey

T1 aquifer - Locality and well numbers

AV3:101436B.APR:99-0266

Figure 9



Department for Water Resources

Northern Adelaide Plains - Groundwater Salinity Survey

T2 aquifer - Locality and well numbers

Government of South Australia

AV3:101436B.APR:99-0267

Figure 10

most of the region. This aquifer averages 20 m in thickness except near the Little Para River where it attains an average thickness of 40–60 m. It comprises very finely grained, poorly consolidated sands. Salinity of groundwater within the aquifer ranges from 600 to 1500 mg/L and occasionally up to between 3000 and 5000 mg/L. However, the aquifer is under-utilised due to problems with well development in the sand and low yields (Shepherd, 1975). Q4 aquifer consists mainly of very fine sand. It is hydraulically connected to the deep Quaternary aquifers but predominantly to the T1 aquifer along the Little Para River.

Historically, water levels of the deep Quaternary aquifer and Tertiary aquifer were above ground throughout most of the area, which suggests that there were upward hydraulic gradients and also a historic upward leakage from deeper aquifers into the overlying shallow Quaternary aquifers.

Extensive pumping from the underlying Tertiary aquifer has reversed the historic head gradient, induced downward leakage and eliminated historic recharge from upward leakage to this aquifer.

The shallow Quaternary aquifers (mainly Q1) in the vicinity of surface drainage, are recharged mainly from winter run off.

4.1.1 Water level trends

Hydrographs of Quaternary aquifers show an almost continuous decline in water levels. The rate of annual decline (and the change in aquifer storage) is controlled by several factors, including;

- rate of recharge
- extraction from the aquifer
- evapotranspiration
- downward leakage and natural discharge.

The decline is thought to be exacerbated by:

- urbanisation and the lining of surface drainage with concrete, both of which reduce the recharge area(s)
- local pumping from the first Quaternary aquifer
- continuous leakage into old corroded sewage pipes
- harvesting surface water up-stream (e.g., Little Para River dam)
- continuous downward leakage via corroded casings into deep aquifers.

Seasonal fluctuations in the pressure of the deep Tertiary aquifer result in simultaneous pressure changes in the overlying Quaternary aquifer(s). It appears that the seasonal water level fluctuations in Quaternary aquifer(s) are caused by pressure transmitted across the confining bed due to seasonal pumping from the Tertiary aquifer. Some seasonal fluctuations are caused by downward leakage in response to pumping from underlying aquifers during the pumping season.

During winter, seasonal fluctuations into Q1 aquifers are apparently caused by infiltration through the riverbed during flow and, possibly, the effects of pressure transmitted across the confining bed from the underlying aquifer and into Q1 aquifer.

4.2 QUATERNARY AQUIFER CONFINING BEDS

The thick sequence of clays in the Hindmarsh Clay Formation acts as a confining layer, which reduces water leakage to or from the underlying Tertiary aquifers

The confining beds between the Quaternary aquifers consist of clay and silt and range in thickness from 5–20 m. These confining beds are absent or thin out in some areas, allowing hydraulic connection between aquifers. This can be observed, for example, between the deep Quaternary aquifers in the Little Para area, the Waterloo Corner area (between the Q4 and T1 aquifers) and in an area several kilometres north of the Gawler River.

A maximum of seven Quaternary confining beds were recognised during the study and designated Cb1 to Cb7 in order of increasing depth, summarised as follows:

- Cb1 overlies the Q1 aquifer
- Cb2 separates the Q1 and Q2 aquifers
- Cb3 separates the Q2 and Q3 aquifers
- Cb4 separates the Q3 and Q4 aquifers
- Cb5 separates the Q4 and Q5 aquifers or Q4 and T1/T2 aquifer(s).
- Cb6 separates the Q5 and Q6 aquifers or Q4 and T1/ T2 aquifer(s).
- Cb7 separates the Q6 aquifer and the underlying first Tertiary aquifer.

In the NAP, Cb5 is the dominant confining bed, separating the Carisbrook Sand aquifer from the underlying Tertiary aquifer.

Several wells were drilled in the region to examine the hydraulic parameters of some of the confining beds. A series of spot cores were collected from predetermined intervals, and laboratory tests were carried out, to determine vertical and horizontal hydraulic conductivities (Gerges, 1997). They showed that vertical hydraulic conductivity varies between 1.5×10^{-4} to 8.6×10^{-7} m/d.

It is significant that cores sampled near the coast (Cb5 and Cb6) have vertical hydraulic conductivity of at least an order of magnitude lower than cores sampled in the east of the basin. The position of the cored wells in relation to the likely sediment source from the east suggests that the eastern sites receive slightly coarser material (silt rather than clay) and therefore have a probability of slightly higher hydraulic conductivities.

However, it should be remembered that these confining beds were sampled and tested approximately 50 years after the commencement of development of the groundwater resource. Since then, the area has been subjected to heavy withdrawals, which have resulted in considerable drawdown in both Tertiary aquifers. It is likely that some consolidation of overlying confining beds will occur, with resultant reduction in porosity and permeability.

4.3 TERTIARY AQUIFER SYSTEM

The underlying Tertiary sediments contain several aquifer systems; each may comprise various subaquifers. Groundwater occurs mainly in the four mostly confined aquifers designated T1, T2, T3 and T4 in order of increasing depth. These aquifers are relatively independent of the stratigraphic units. Their distribution and characteristics depend largely on the depositional environment, the major structure, movements along major faults and the general geological history of the area.

The aquifers exhibit large variations in thickness, lithology, salinity distribution and yield. The first and second Tertiary aquifers (T1 and T2) are recognised as superior aquifers in terms of salinity and yield. Consequently, this study has focused on both aquifers and their relationship with other aquifers.

Preliminary water balance calculations were attempted for T2 aquifer only, from where the majority of the area's extractions occur. Water balance calculations for the T1 aquifer have not been attempted at this stage, since it would include the southern pumping centres of the Adelaide Metropolitan area where the majority of extraction from this aquifer occurs. In addition, recharge to this aquifer involves a second flow path generated in the Adelaide Metropolitan area. Future proposals will examine the water balances of both aquifers.

4.3.1 First Tertiary aquifer (T1)

The first Tertiary aquifer (T1) is defined as the first intersected, saturated and permeable Tertiary sediments. Apart from an area located a few kilometres north of the Gawler River, where drillhole records indicate the Q4 aquifer directly overlies the T2 aquifer, this definition is regardless of the aquifer's stratigraphic age. T1 aquifer may therefore consist of several stratigraphic units, varying in lithology and thickness. These sediments may include the overlying Carisbrook Sand (Q4), which underlies the Quaternary clay.

T1 aquifer is the main source of irrigation water in the area south of Waterloo Corner. The aquifer is contained in the Dry Creek Sands and the Port Willunga Limestone. It is wedge shaped with an average thickness of 70 m in the south, and thinning as it nears Gawler River. Salinity ranges from 600–2000 mg/L with the lowest salinity near the Little Para River to the south. The aquifer is hydraulically connected to the deep Quaternary aquifer (Q4) and separated from the underlying aquifer by a layer of clay (Munno Para Clay) which extends over the entire area south of the Gawler River.

The first Tertiary aquifer in this area consists of two major subaquifers (Gerges, 1987, 1997):

- Subaquifer T1a, consists of Hallett Cove Sandstone and Dry Creek Sand, and the permeable portions of the 'Croydon facies' and may include the Carisbrook Sand of the Q4 aquifer (along Little Para River area only).
- Subaquifer T1b, consists of limestone of the Port Willunga Formation, separated from the underlying second Tertiary aquifer by a confining bed called the Munno Para Clay Member. This forms the base of the T1 aquifer.

Both subaquifers are separated by a semi-confining bed comprising the remaining part of Croydon facies.

4.3.1.1 GROUNDWATER EXTRACTION AND POTENTIOMETRIC SURFACE

Current potentiometric surface maps have been constructed from water level measurements taken from the observation well network (Fig. 7). The increase in the number of observation wells in the area has enabled the extent of the cone of depression to be better defined. In this report, the term 'cone of depression' is defined as the area below the zero AHD contour.

Water level measurements taken annually in September have been considered representative of the winter potentiometric surface, while measurements taken in March have been considered representative of the summer potentiometric surface.

The potentiometric surfaces for T1 aquifer during the summers of 1988–89, 1991–92, 1997–98 and 2000–01, are shown in Figures 11–14.

In the southern parts of the NAP, most of the groundwater extraction occurs from subaquifers T1a and T1b. At present, most of the production wells are completed in the T1b subaquifer because of its sand-free water supply. Groundwater quality from this subaquifer is generally suitable for the required purposes.

Extractions from T1 aquifer occur from three distinctive areas:

- Little Para River (irrigation) area
- Penrice (ICI) — SAMCOR
- The Waterloo Corner area.

Little Para River (irrigation) area

This area contains 49 production wells pumping between 525 and 638 ML during the 210 days of summer. In addition, 13 wells pump a total of 87 ML during summer from the Carisbrook Sand aquifer.

Pumping from this area affects the shape of the potentiometric surface in the 'Penrice (ICI) — SAMCOR' industrial pumping centre during summer.

The recent urbanisation of the Little Para River area during the early 1990's caused a considerable shift of groundwater licence allocations with approximately 300–350 ML transferred to other areas, such as Waterloo Corner.

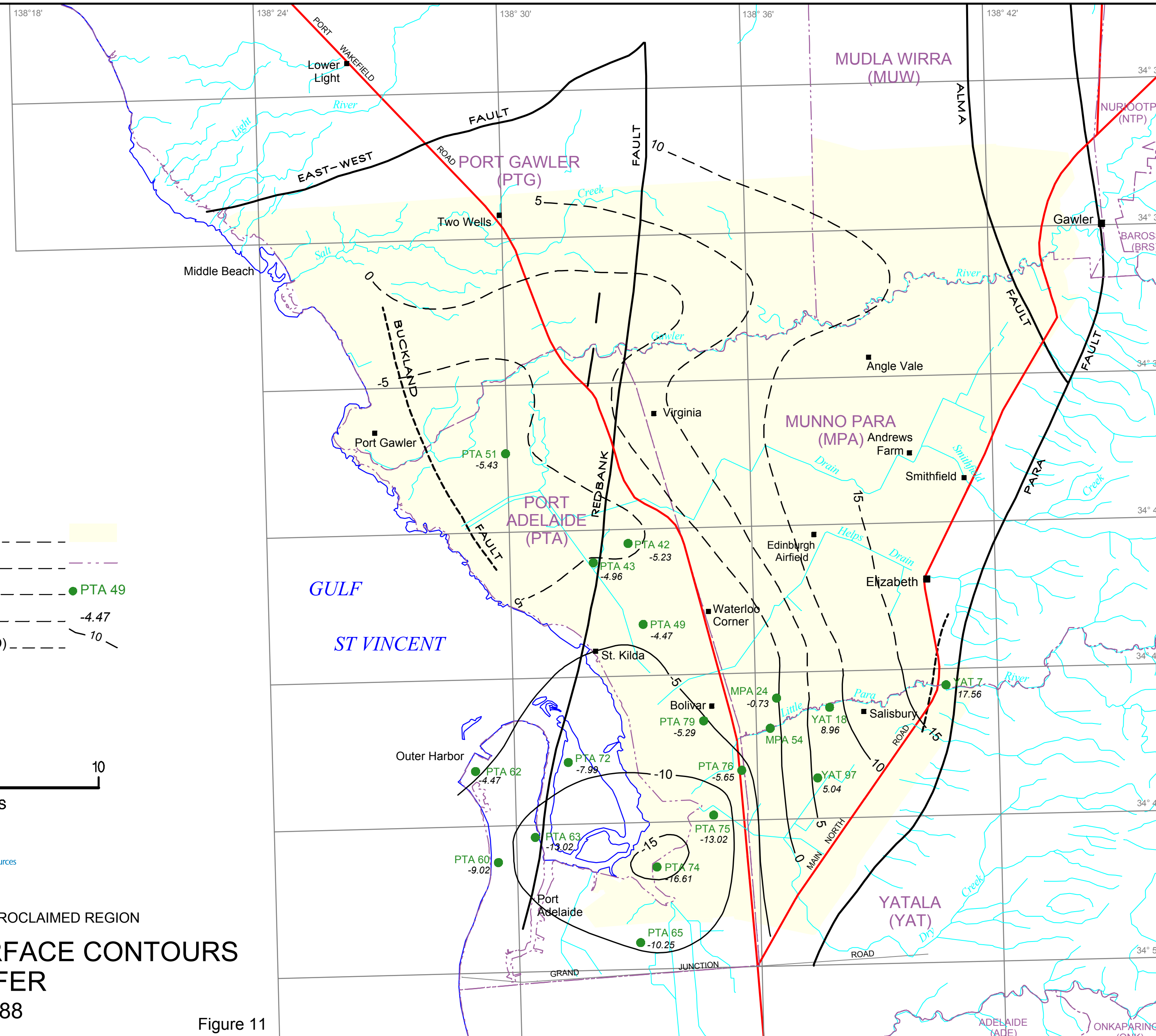
Penrice (ICI) — SAMCOR

The extraction of groundwater from Penrice (ICI) — SAMCOR began in 1957. Most of the groundwater in this area is used for industrial purposes. This pumping centre (the largest and most permanent in the area) contains 12 production wells pumping 2700–3000 ML/yr. The present rate of pumping has created a steep cone of depression over the whole year, which expands to its maximum level during summer. The levels are approximately -20 m AHD in the central area (Fig. 13) contracting slightly during winter to -16 m AHD.

During summer, the large withdrawals from the aquifer produce seasonal variations in the regional flow pattern, creating a groundwater divide between the Penrice (ICI) — SAMCOR permanent cone and the Metropolitan area (West Lakes) seasonal cone to the south.

During winter, the location of the permanent cone of depression corresponds to the location of recently developed pumping centres. At present, the cone of depression decreases to its minimum size at the end of winter but the potentiometric surface never recovers to its pre-pumping levels for the following reasons:

- There is continuous industrial pumping during winter with no recovery period.
- The effect of the cumulative drawdown over years of pumping.



LEGEND

Northern Adelaide Plains Proclaimed Region

Hundred boundary

Observation well and number — PTA 49

Potentiometric level (metres AHD) — -4.47

Potentiometric surface contours (metres AHD) — 10

0 5 10

KILOMETRES

Department for Water Resources

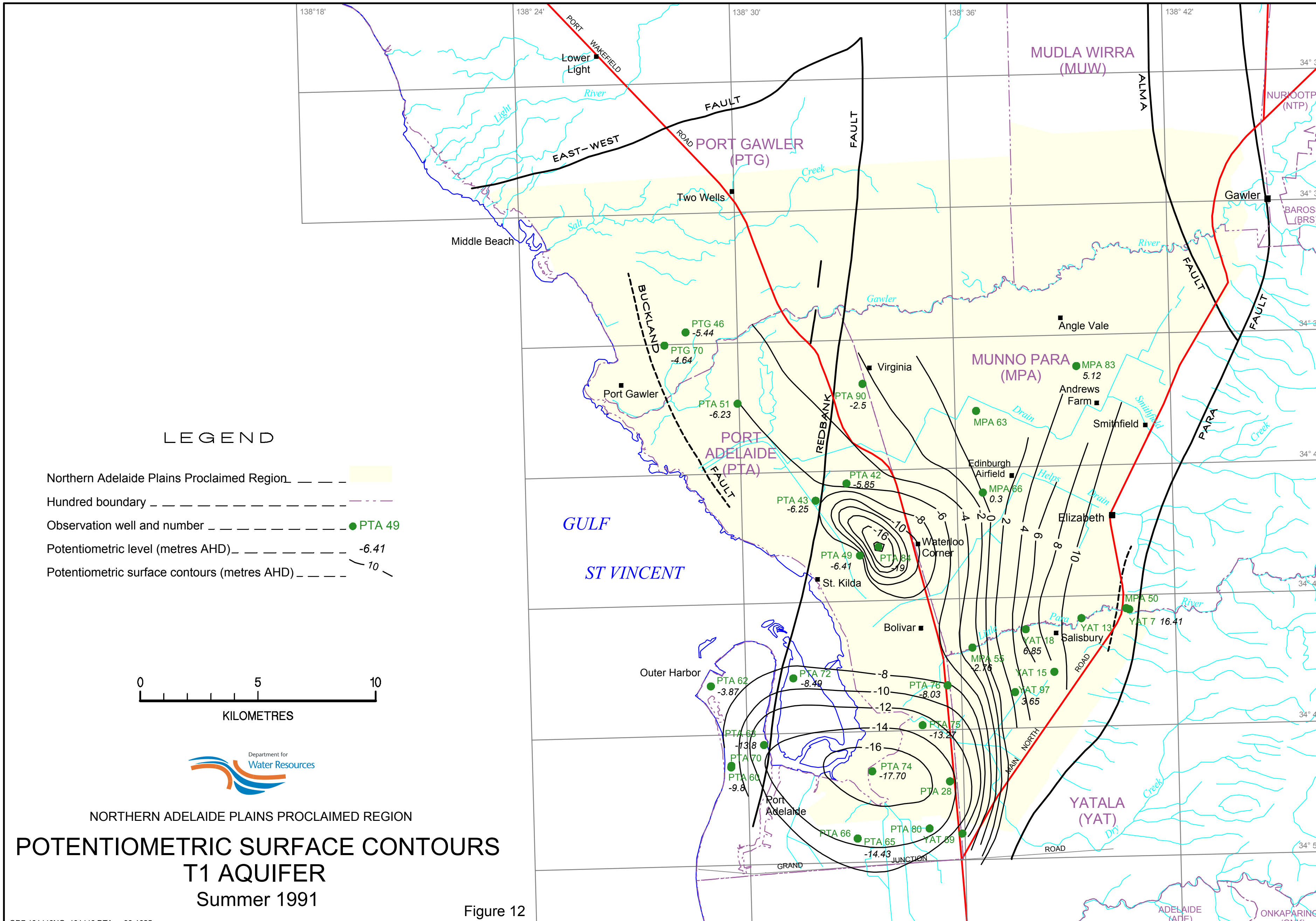
NORTHERN ADELAIDE PLAINS PROCLAIMED REGION

POTENTIOMETRIC SURFACE CONTOURS
T1 AQUIFER

March 1988

Figure 11

QD7 101446NG: 101446.DTA 98-1624



LEGEND

Northern Adelaide Plains Proclaimed Region

Hundred boundary

Observation well and number — PTA 49

Potentiometric level (metres AHD) — -6.41

Potentiometric surface contours (metres AHD) — 10

0 5 10 KILOMETRES

Department for Water Resources

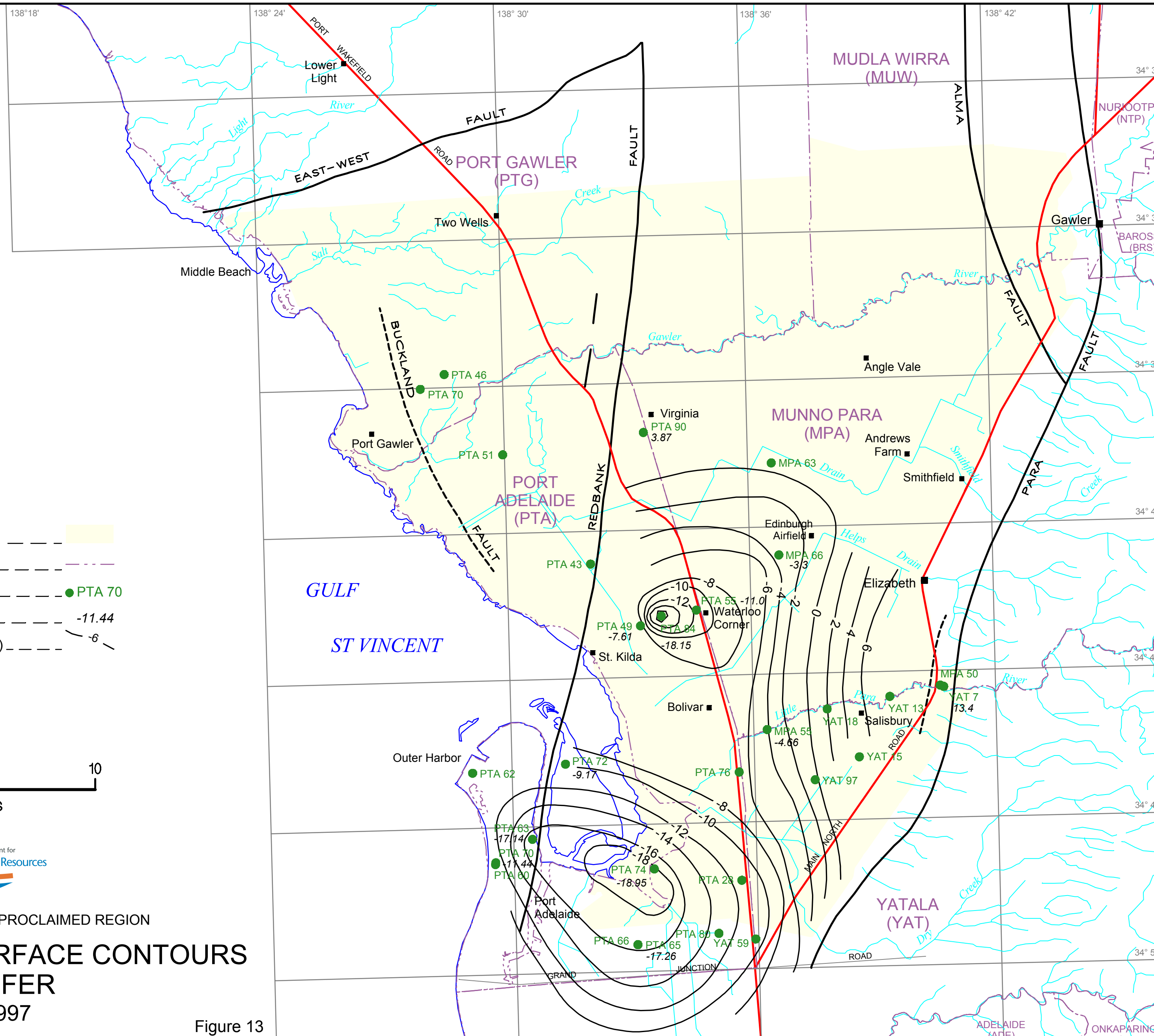
NORTHERN ADELAIDE PLAINS PROCLAIMED REGION

POTENTIOMETRIC SURFACE CONTOURS T1 AQUIFER

Summer 1991

Figure 12

QD7 101446NG: 101446.DTA 98-1625



LEGEND

Northern Adelaide Plains Proclaimed Region	
Hundred boundary	
Observation well and number	PTA 70
Potentiometric level (metres AHD)	-11.44
Potentiometric surface contours (metres AHD)	-6

0 5 10
KILOMETRES

Department for Water Resources

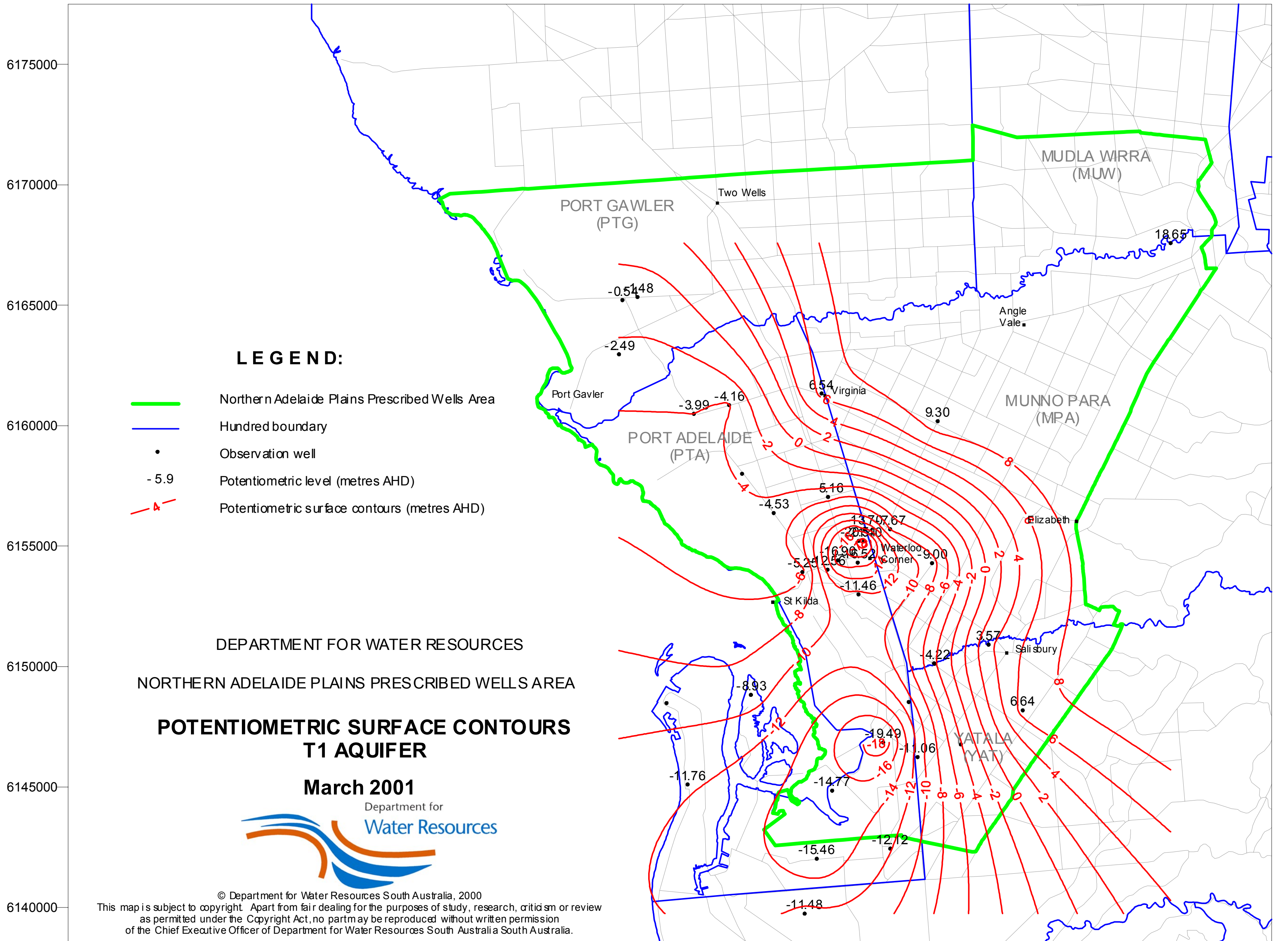
NORTHERN ADELAIDE PLAINS PROCLAIMED REGION

POTENTIOMETRIC SURFACE CONTOURS T1 AQUIFER

Summer 1997

Figure 13

QD7 101446NG: 101446.DTA 98-1626


LEGEND:
Northern Adelaide Plains Prescribed Wells Area
Hundred boundary
Observation well
- 5.9 Potentiometric level (metres AHD)
Potentiometric surface contours (metres AHD)
DEPARTMENT FOR WATER RESOURCES
NORTHERN ADELAIDE PLAINS PRESCRIBED WELLS AREA
POTENTIOMETRIC SURFACE CONTOURS
T1 AQUIFER
March 2001
Department for Water Resources
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PORT GAWLER (PTG)
MUDLA WIRRA (MUW)
MUNNO PARA (MPA)
PORT ADELAIDE (PTA)
YATALA (YAT)
Two Wells
Angle Vale
Port Gavler
Virginia
Elizabeth
Waterloo Corner
St Kilda
Salisbury
6175000
6170000
6165000
6160000
6155000
6150000
6145000
6140000
245000
250000
255000
260000
265000
270000
275000
280000
285000
290000
295000

Figure 14

Extensive and continuous pumping from this area has created a regional cone of depression that has changed local flow patterns to a radial flow from all directions toward the centre of the cone. This includes flow from under Gulf St Vincent, to the west.

The Waterloo Corner area

T1 aquifer is the main source of irrigation water in the area south of Waterloo Corner where there is an approximate total extraction of 1225 ML/yr. The aquifer is contained in the Dry Creek Sands and the Port Willunga Limestone. Salinities range from 600 to 2000 mg/L with the lowest salinity near the Little Para River to the south. This aquifer is separated from the Quaternary aquifer (Q4) by a leaky confining bed and separated from the underlying T2 aquifer by a layer of clay (Munno Para Clay), which extends over the entire region.

In the Waterloo Corner area, previous investigations (Selby and Gerges, 1981) have shown that under intensive pumping, aquifer T1 can become contaminated by downward movement of more saline water from the overlying aquifers. By contrast, aquifer T2 is effectively separated from T1 aquifer by the Munno Para Clay, except in areas where dual aquifer completion wells occur.

During the last decade, the water resource agencies have carried out hydrogeological investigations in the Waterloo Corner area in response to complaints of increasing groundwater salinities. The initial investigations (Selby and Gerges, 1981) reveal that:

- The T1 aquifer, at approximately 58 m below ground, contained groundwater with salinity ranging between 800–1000 mg/L.
- At 40–58 m, the overlying Q4 aquifer salinities range between 1820 mg/L (lower part of Q4 (Q4b)) to 4850 mg/L (upper portion of Q4 (Q4a)).
- The confining bed separating both aquifers (Q4 and T1) is fragile, and consists of silt, carbonaceous material and minor clay. Some early inappropriate drilling and well development have resulted in hydraulic interconnections between the Q4 and T1 aquifers. This has lead to breeches in the confining beds separating both aquifers.
- Before development, the potentiometric water levels in both T1 and T2 aquifers were slightly higher than that of the Q4 aquifer, indicating an upward hydraulic flow. Subsequent extraction by users in the area has led to the potentiometric water level of T1 aquifer becoming lower than the Q4 aquifer and other Quaternary aquifers. Given that the confining bed separating the T1 and Q4 aquifers is fragile, the T1 aquifer, as a result, has experienced a considerable increase in salinity due to downward leakage from Q4.
- The rate of downward leakage depends on the thickness, distribution and lithology of the confining bed separating T1 aquifer from Q4 aquifer and on the gradient between Q4 and T1 aquifers. In some areas (as shown in this example), this could significantly affect the salinity of the T1 aquifer.
- The groundwater salinity and water level of T2 aquifer in the Waterloo Corner area was always higher than T1 aquifer. Some early poor drilling and completion methods resulted in interconnections between the T1 and T2 aquifers.

Recently a significant salinity problem in the T1 aquifer has occurred north of the Waterloo Corner area, forcing irrigators to backfill their wells in the T1 aquifer and use the T2 aquifer, despite its higher salinity.

The shift of groundwater license allocations to the Waterloo Corner area, because of urbanisation of the Little Para River, has led to additional stress on this fragile aquifer. It will cause a lowering of water levels accompanied by leakage of more saline water into the T1 aquifer. There will be continuing detrimental effects on licensed users.

4.3.1.2 SALINITY DISTRIBUTION IN THE FIRST TERTIARY AQUIFER

Water quality data from local wells was examined and validated before being used for analysis and interpretation. Most of this data was collected before the 1950s and assumed to represent the historic salinities within this aquifer. Salinity information from both subaquifers (T1a and T1b) are used in data analysis of the T1 aquifer.

Figure 15 shows the salinity distribution within T1 aquifer. Low salinity groundwater of less than 800 mg/L occurs in two major regions — a northern region located immediately south of the Gawler River and a southern region surrounding the Little Para River and extending to Waterloo Corner and the St Kilda area.

It is important to note that the areal extent of this low salinity water is much larger than in any of the overlying Quaternary aquifers, suggesting that recharge to the T1 aquifer does not occur as a result of downward leakage. In any event, the potentiometric level in the T1 aquifer has been historically higher than that observed in the overlying Q4 aquifer, indicating an upward hydraulic gradient rather than downward leakage.

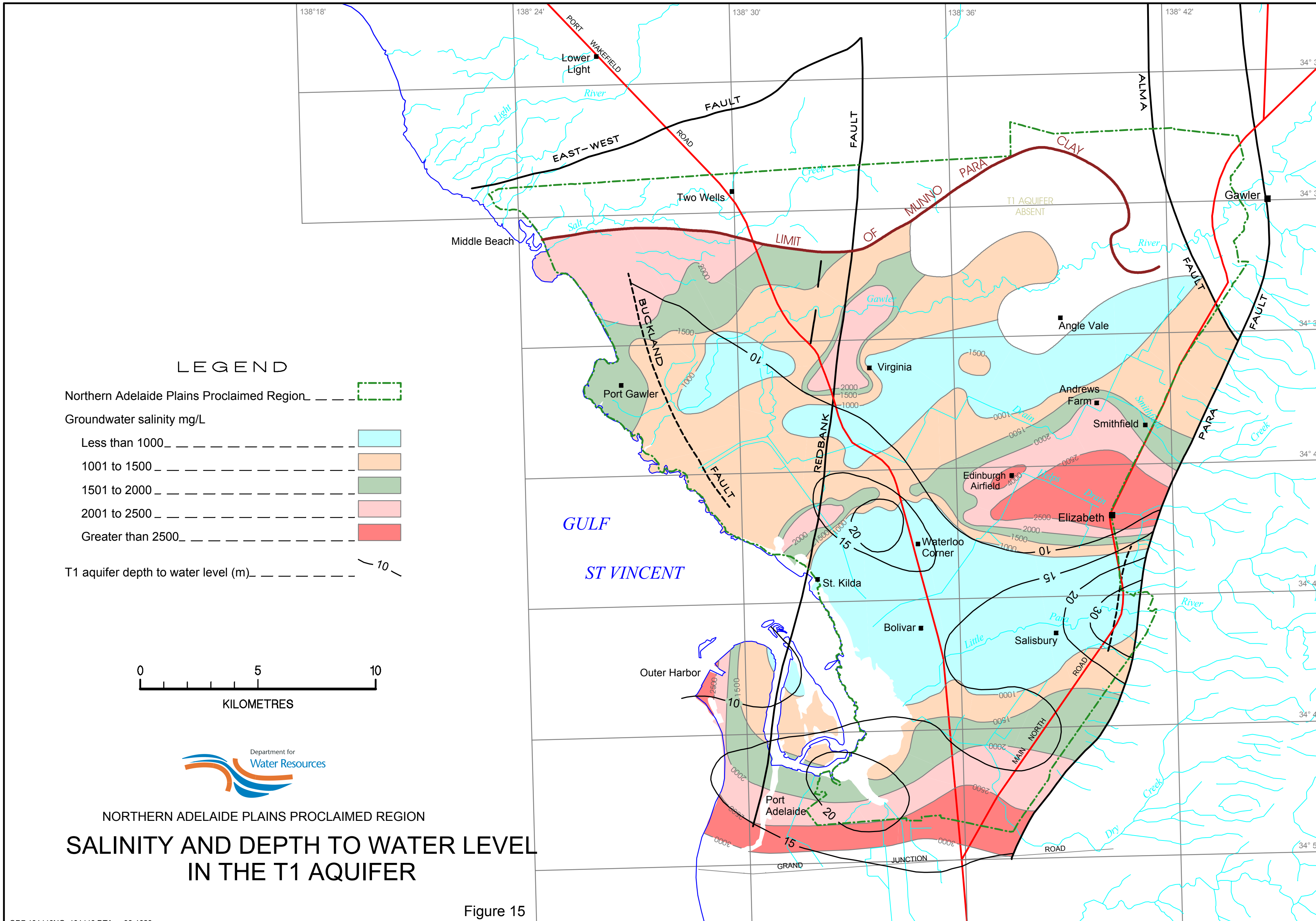
4.3.1.3 SALINITY TRENDS

Generally, average water salinity in the T1 aquifer has increased by between 200 and 800 mg/L, and occasionally up to 6000 mg/L over the last 30 years of pumping, particularly near Waterloo Corner. The major reasons for these increases are:

- Point source leakage from overlying saline Quaternary aquifers due to corroded casing (a major contributor).
- Lateral flow from highly saline areas.
- Downward leakage in areas where the confining beds separating the Tertiary aquifers from the Quaternary aquifers are thin or non-existent.
- Leakage from the T2 in dual aquifer completion wells.
- Potential upward leakage from the T2 to T1 aquifers in the Waterloo Corner and Penrice Soda areas where it is thought that the Munno Para Clay is a poor confining layer.

4.3.1.4 WATER LEVEL TRENDS

Selected hydrographs from the heavy pumping areas where long-term records exist (Figs 16–19) show seasonal fluctuations and overall decline during the period of record availability. The decline averages 0.6 m/yr and is primarily due to extensive pumping from this production aquifer (T1). Extensive pumping induces increased hydraulic gradient in the production aquifer, which promotes increased lateral flow and vertical leakage due to reversed vertical gradient. Increased lateral flow and leakage have potential negative impacts on the long-term salinity within the T1 aquifer.



NORTHERN ADELAIDE PLAINS PROCLAIMED REGION

SALINITY AND DEPTH TO WATER LEVEL IN THE T1 AQUIFER

Figure 15

QD7 101446NG: 101446.DTA 98-1623

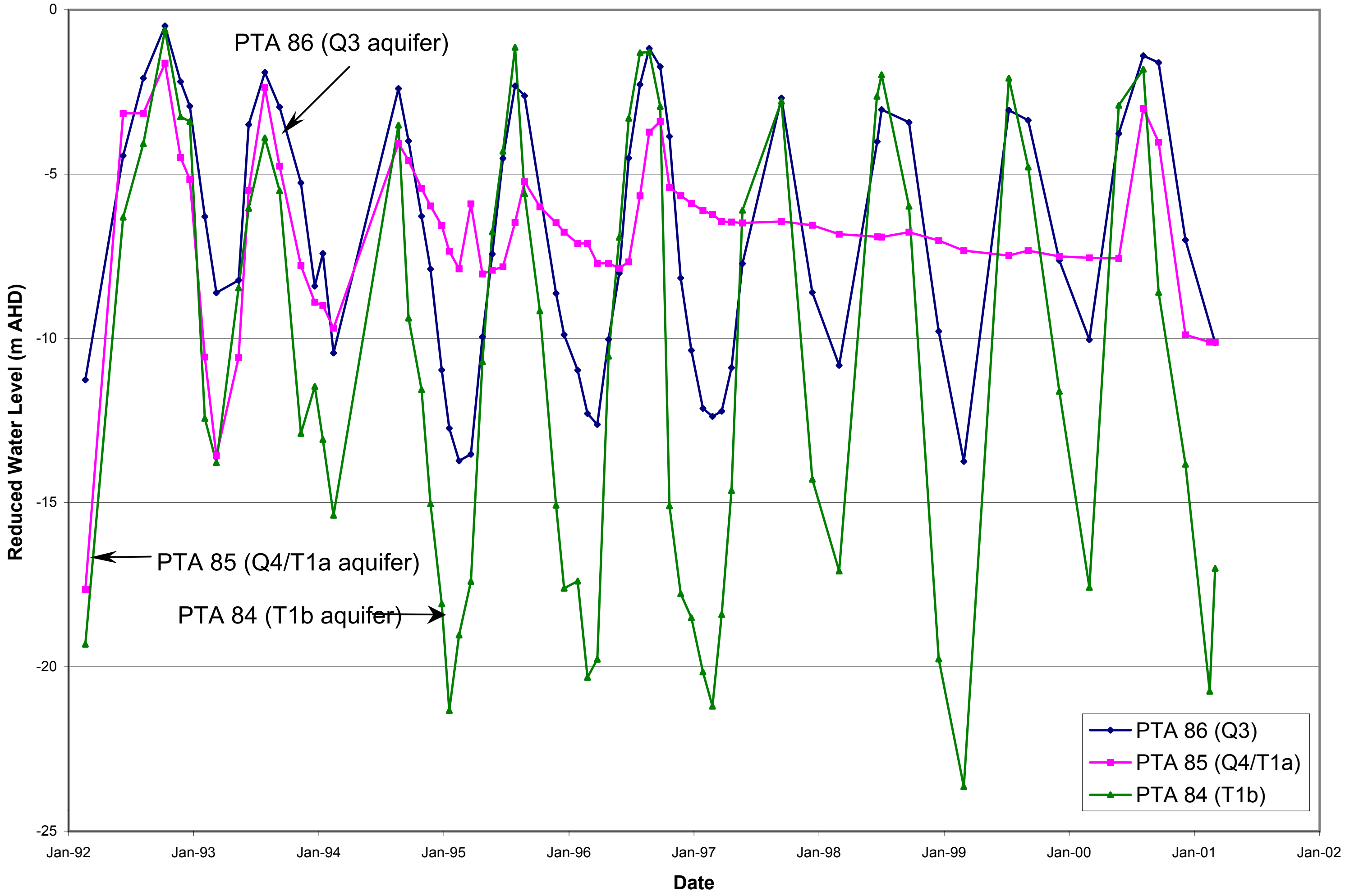


Figure 16 Hydrographs PTA 86 (Q3); PTA 85 (Q4/T1a) & PTA 84 (T1b)

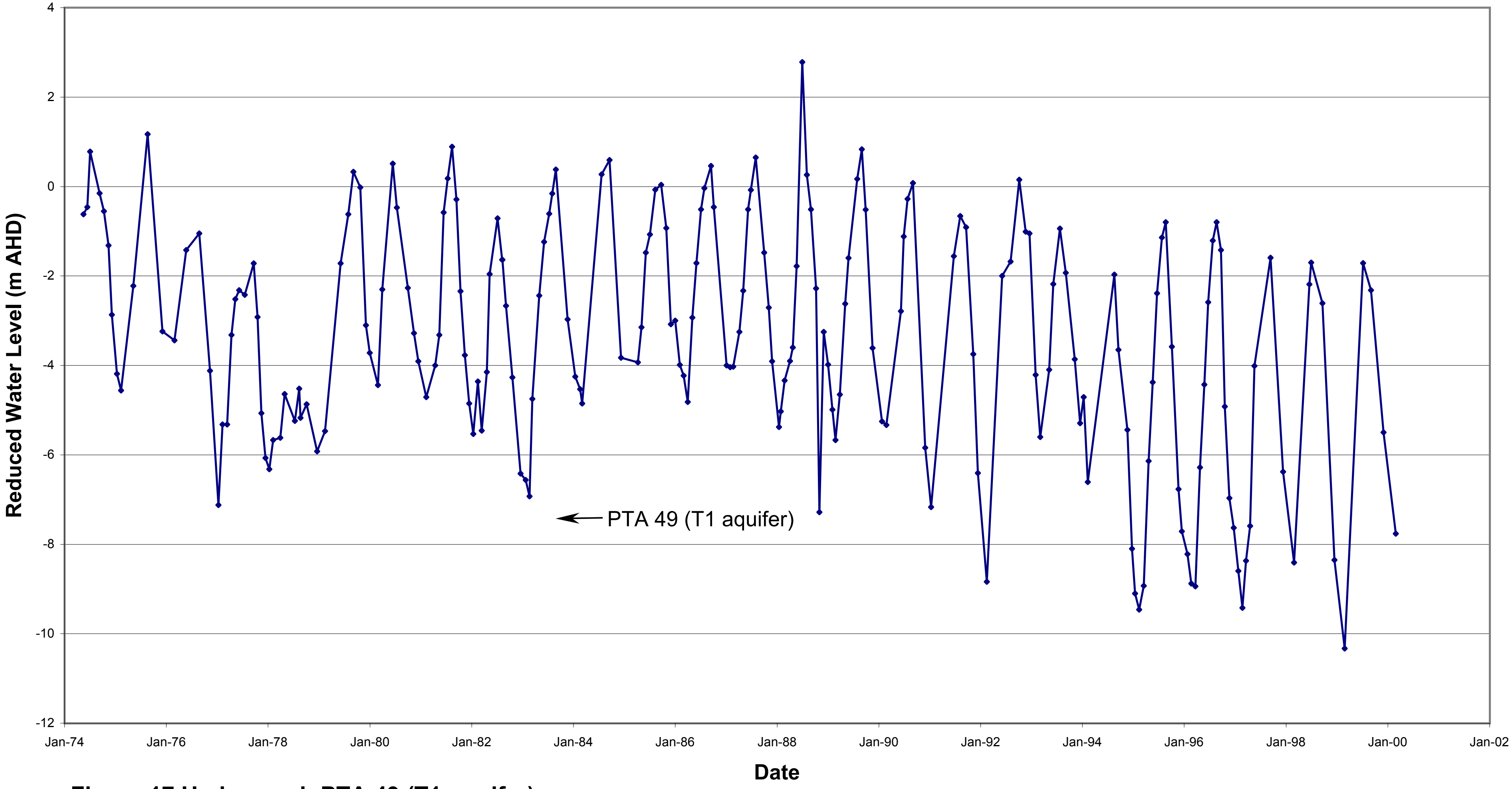


Figure 17 Hydrograph PTA 49 (T1-aquifer)

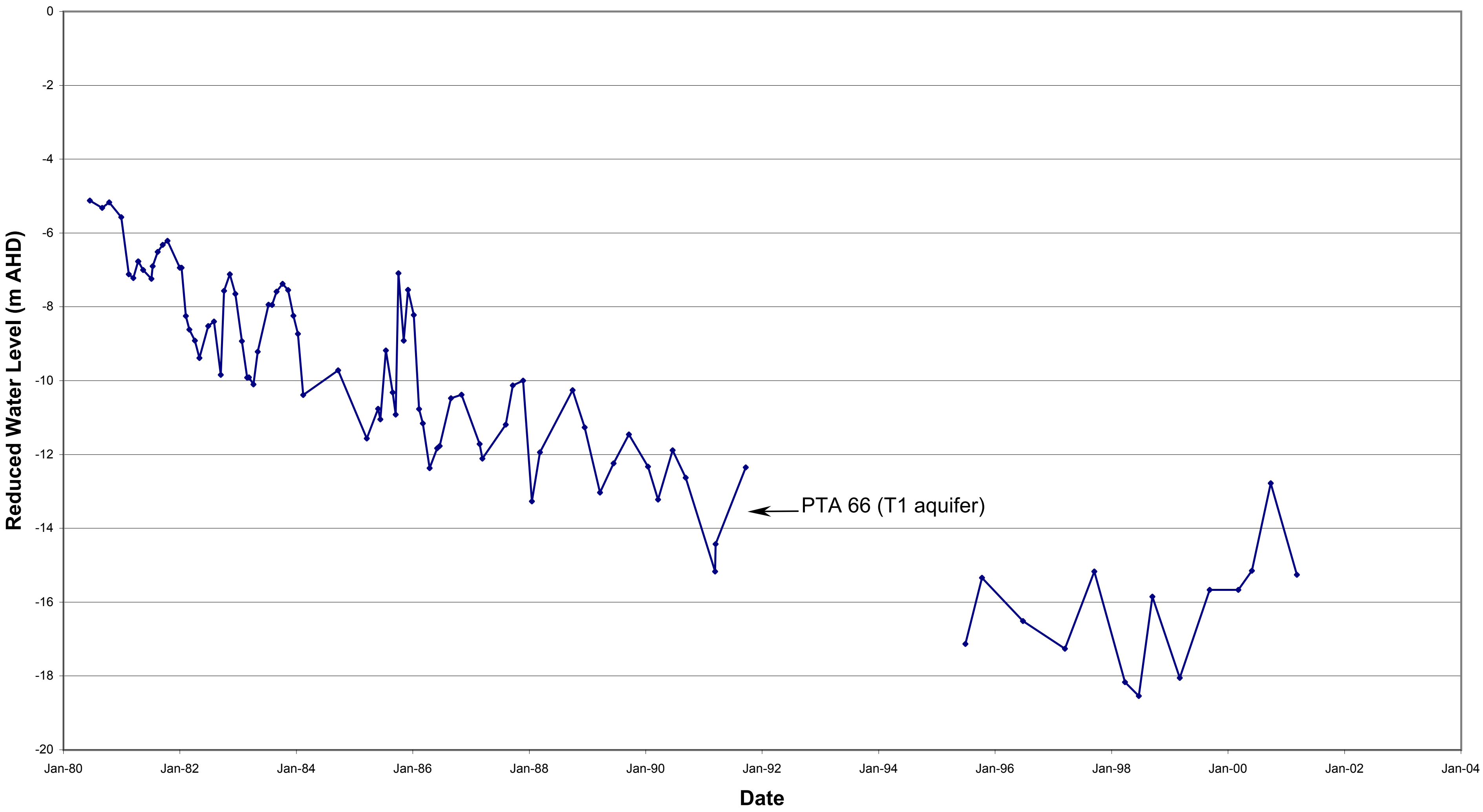


Figure 18 Hydrograph PTA 66 (T1-aquifer)

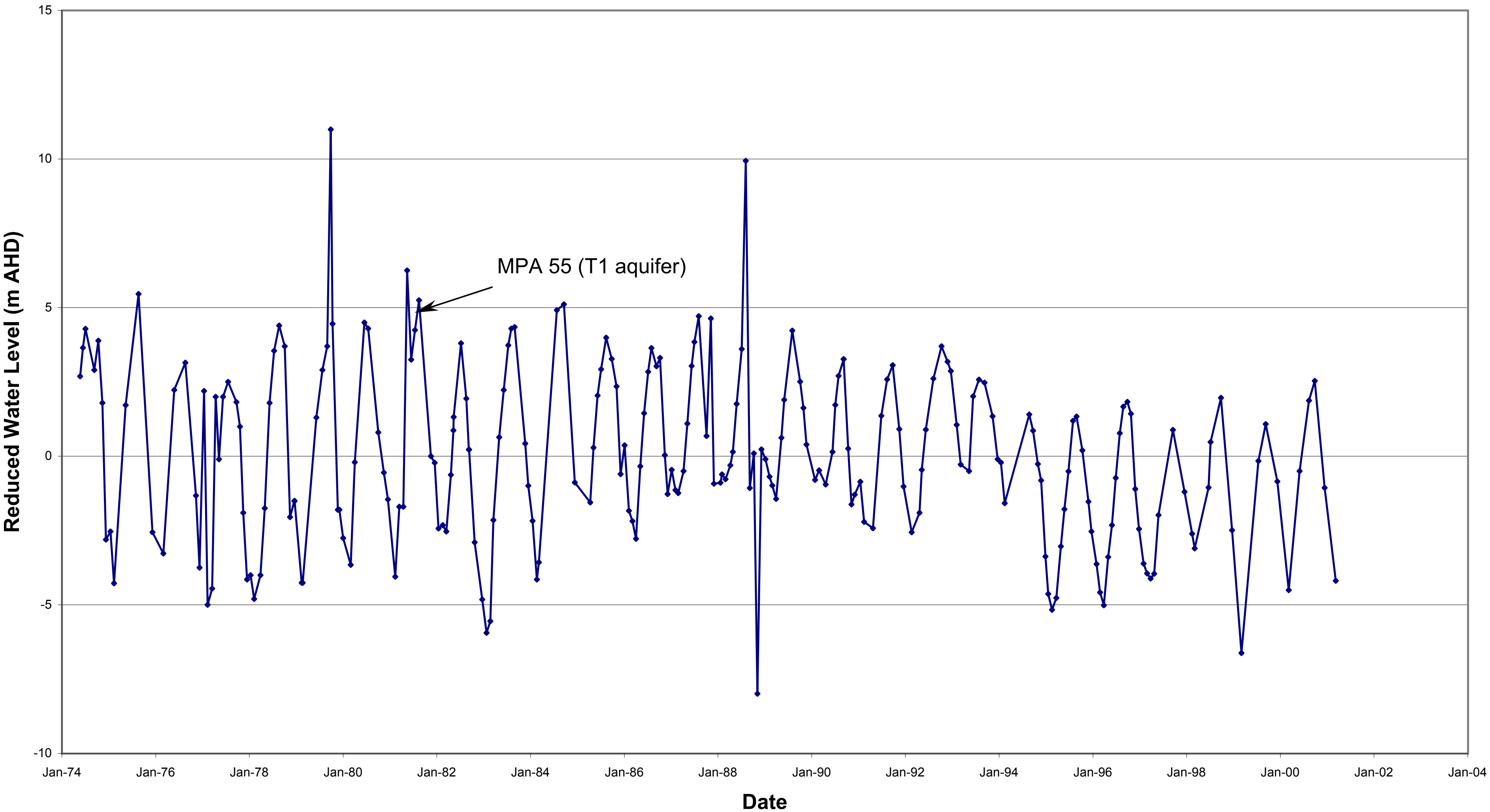


Figure 19 Hydrograph MPA 55 (T1 aquifer)

A cone of drawdown approximately 25-30 m deep has formed below the Waterloo Corner area. This is in response to:

- Intensive pumping which has caused the development of a steep cone of depression during summer that does not recover completely during winter.
- A concentration of pumping wells in a small area, which causes well interference.
- The relatively small lateral flow (relative to the transmissivity of the aquifer).
- Pumping during winter from the industrial pumping centre.

4.3.1.5 AQUIFER PARAMETERS

The first Tertiary aquifer was previously described as one homogenous aquifer with an average transmissivity of 60 m^2/d (Shepherd, 1975).

Recent studies, particularly in the southern area, have indicated T1 to be a multi-layered aquifer with two significant subaquifers, T1a and T1b. In these studies aquifer and confining bed parameters were determined from aquifer test data using the type curve matching (log/log) and Jacobs straight line (semi-logarithmic) methods (Gerges, 1992, 1995, 1996, 1997). Flow net analysis methods were used (Gerges, 1997) where possible to calculate the apparent transmissivity of the aquifer.

The results suggest the presence of a moderately effective confining bed indicating hydraulic separation between T1a and T1b sub-aquifers. These results also suggest that the transmissivity values range between 80 and 150 m^2/d, and the storage coefficients between 2.5 x 10^{-4} and 5 x10^{-4} .

4.3.2 Confining bed between T1 and T2 aquifers

The Munno Para Clay Member consists of 6–8 m of dark-grey clay interbedded with two bands of pale-grey limestone, containing water with a salinity close to the average salinity of aquifers T1 and T2.

Laboratory testing of cores taken from the clay in several locations suggests that the clay is of very low permeability. In the Wingfield area, the vertical permeability averages 1.6 x 10^{-5} m/d (Gerges, 1982). Recent drilling at several locations in the NAP shows a variation in vertical permeability of between 10^{-6} and 10^{-7} m/d (Gerges, 1997).

The confining beds were sampled and tested approximately 50 years after commencement of development of the groundwater resource. The area has been subjected to heavy withdrawals, which have resulted in considerable drawdown in both Tertiary aquifers. Some settlement of overlying confining beds, with resultant reduction in porosity and permeability seems likely.

4.3.3 Second Tertiary aquifer (T2)

The Second Tertiary aquifer comprises the second intersected, saturated and permeable Tertiary sediments, regardless of their stratigraphic age. The T2 aquifer occurs throughout the entire zone. It consists of well-cemented limestone of lower Port Willunga Formation. The formation lies relatively flat and is uniform in thickness, varying between 80–120 m.

In the Allenby Gardens Well (Gerges, 1980a), North Glenelg Well (Gerges, 1980a), Wingfield Well (Gerges, 1982) and the Andrews Farm site (Gerges et al., 1994) all subaquifers are well recognised.

Evidence from lithological and geophysical logs confirms the presence of three major divisions in this aquifer, recognised as subaquifers T2a, T2b and T2c (Gerges, 1980a, b, c). Subaquifer T2a is mostly pale-grey to white well-cemented limestone/sandstone, with groundwater of salinity between 600 and 3590 mg/L (Wingfield). Subaquifer T2b is well recognised as a pale-yellow to orange–brown limestone–sandstone, friable to moderately cemented and occasionally interbedded with highly calcareous, fossiliferous sand. In some areas, it may contain groundwater inferior to the overlying T2a subaquifer, which ranges in salinity from between 600 mg/L at Angle Vale, 4840 mg/L at Wingfield and 8000 mg/L at North Glenelg.

Subaquifer T2c consists mainly of interbedded sand and very friable limestone with occasional silt and clay. It is well recognised in the Northern Adelaide area particularly at the Andrews Farm site (Gerges 1994) and other sites (Gerges, 1994, 1996; Gerges et al., 1996).

In the Virginia area the limestone aquifer consists mostly of pale-grey, dense limestone with relatively moderate- to low-transmissivity.

In the area north of the Gawler River and east of the Redbank fault, the Munno Para Clay and the T1 aquifer are not present and the Q4 aquifer overlies the T2 aquifer, which consists mainly of T2b and T2c subaquifers. Well yields in this area are typically very good, suggesting a high aquifer transmissivity. Most of the production wells in this area are completed in the upper part of the T2 aquifer. During well development, removal of sand and the weakly cemented material from the top of the aquifer, creates vertical inter-connections with the overlying saline, Q4 aquifer. Consequently, this exacerbates the downward leakage of saline groundwater into the T2 aquifer.

An investigation well (PTG 78) drilled in this area, and completed in the lower part of the T2 aquifer, shows a salinity of 1200 mg/L which is significantly lower than surrounding production wells.

In the area between the Alama Fault and the Para Fault, the T2 aquifer lithology suggests that it consists mostly of undifferentiated sand and minor clay, similar to the lithology of subaquifer T2c.

In the area north of Gawler River bounded by the Redbank fault, and extending to the town of Two Wells, the confining bed of Munno Para Clay is missing and the T1 aquifer immediately overlies the T2 aquifer, forming virtually one aquifer.

In some areas, a sand problem exists which necessitates prolonged aquifer development at a higher rate.

4.3.3.1 GROUNDWATER EXTRACTION AND POTENTIOMETRIC SURFACE

Available data suggests that before the 1950s, most of the wells were flowing with a potentiometric surface approximately 10 m above ground level. This was particularly the case in the area that lies between the Little Para and Gawler Rivers and in the vicinity of the coast. The general flow direction was mainly westward (Fig. 20). These flow directions are similar to those deduced from the overlying T1 aquifer.

Significant pumping occurs from this aquifer in Virginia, Angle Vale and the area north of Gawler River. Consequently, the water level in these areas has declined by between 50–70 m at their centres.

Extraction from this aquifer has been constant over the last 10–15 years. During summer it is approximately 10 000 ML/yr, which is almost three times the winter extraction rate of approximately 3500 ML/yr (Fig. 3).

Available potentiometric surface information suggests a continuous expansion and steepening of the cone of depression over the years of pumping. This has modified the local flow patterns into a radial flow from all directions toward the centre of the cone. Figures 21 and 22 show the potentiometric surface for the summers of 1970 and 1988, while Figures 23 and 23a show the most recent potentiometric surface derived during the summer of 1998 and 2001.

Heavy extraction occurs from the Virginia area, resulting in high well interference. Consequently, a depletion of elastic storage and the development of a pronounced cone of depression during summer have occurred. This steep cone of depression, which does not recover completely during winter (Figs 24 and 24a), is a result of the high extraction and the inability of the aquifer to transmit water into its centre, where the highest concentration of pumping wells occur. Consequently, the area has suffered a massive reduction in pressure that translates to a decline of up to 70–75 m in the potentiometric surface at the centre of the cone.

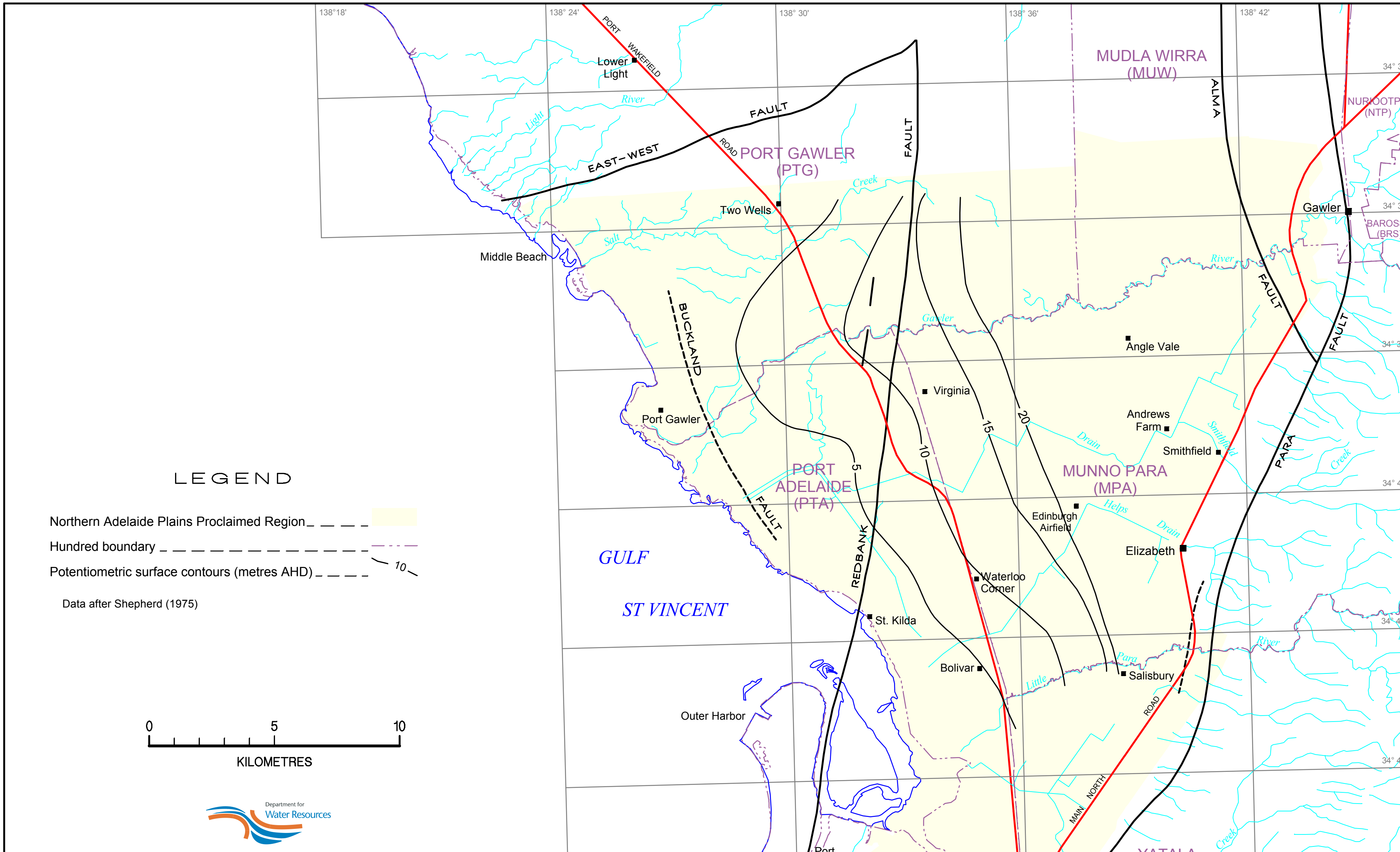
Currently during summer, the cone of depression of the T2 aquifer reaches the top of the aquifer creating a short-term unconfined situation in the Virginia area. It is expected that if present levels of extraction are maintained, water levels will continue to decline throughout this area. Monitoring data from observation wells located in the centre of the cone (MPA 109, Fig. 25; PTA 47, Fig. 26; and MPA 64, Fig. 27) over the last few years support this predicted trend.

The current decline in water levels may continue outside the centre of the cone. However, as the cone progressively expands, the unconfined situation will spread laterally over a large portion of the irrigated area, until it reaches a new equilibrium between inflows and outflows. This is consistent with previous conclusions from the Adelaide Metropolitan area modelling (Gerges, 1999). Recent water levels recorded from monitoring wells located outside the heavy pumping area also partly support this conclusion. (PTG 62, Fig. 28; PTG 53, Fig. 29; MPA 75, Fig. 30; and MPA 81, Fig. 31).

The current regional flow in the Penrice area is now predominantly towards the north, which indicates that the potentiometric surface has been significantly modified by pumping from the T2 aquifer in the Virginia area, some 20–30 km north of Adelaide.

The loss of head from the T2 aquifer over the last 40–50 years is 40–70 m in the centre of the cone (the Virginia area) and approximately 12 m in the rest of the area.

The heavy extraction from the NAP will contribute, in the long term, to a decline in water levels in non-pumping areas, a steepening of the hydraulic gradient and a modification of the direction of flow.



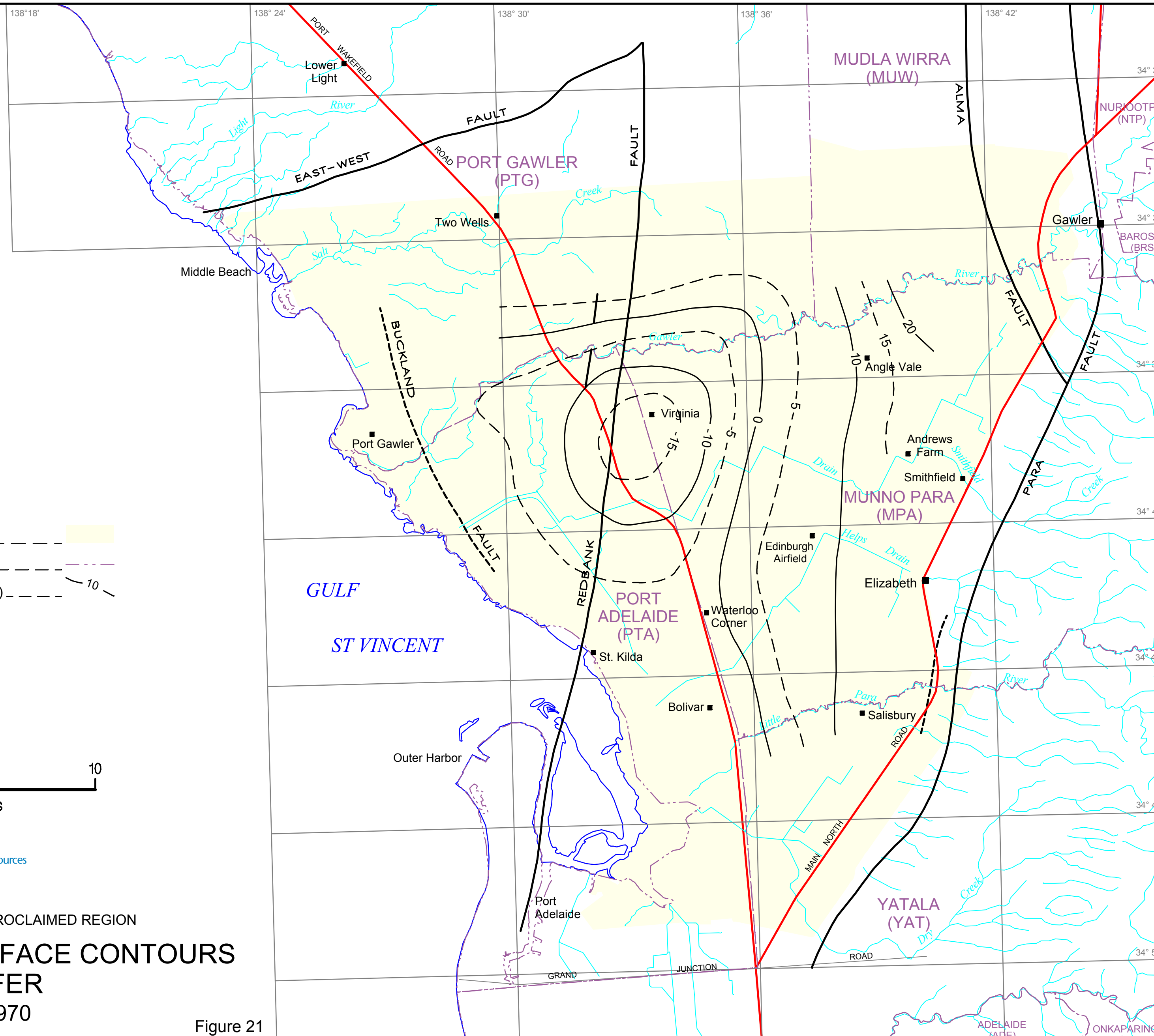
NORTHERN ADELAIDE PLAINS PROCLAIMED REGION

POTENTIOMETRIC SURFACE CONTOURS TERTIARY AQUIFER

September 1959

Figure 20

QD7 101446NG: 101446.DTA 98-1632



LEGEND

North Adelaide Plains Proclaimed Region

Hundred boundary

Potentiometric surface contours (metres AHD) — 10 —

Data after Shepherd (1975)

0 5 10

KILOMETRES

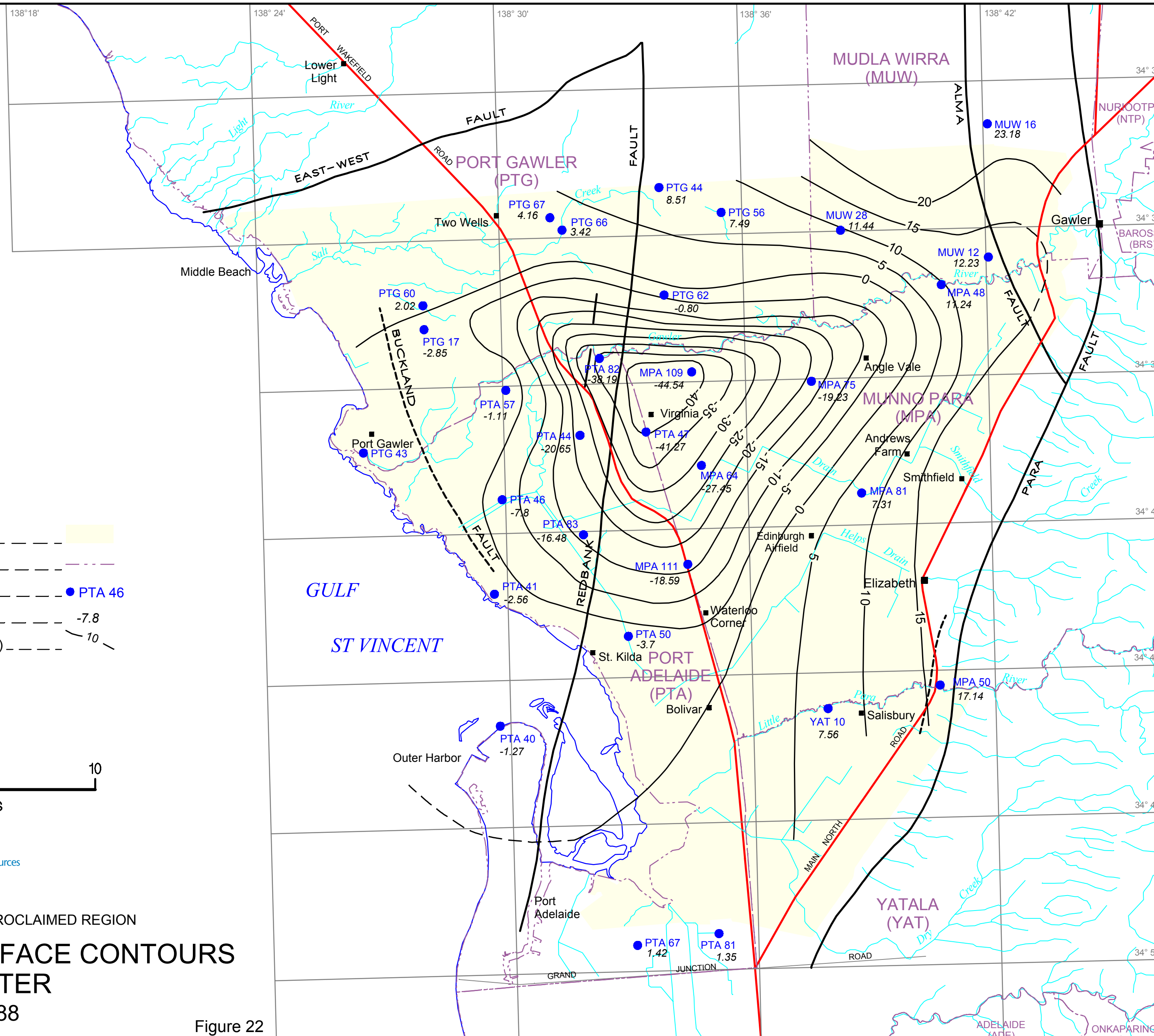
Department for Water Resources

NORTHERN ADELAIDE PLAINS PROCLAIMED REGION

POTENTIOMETRIC SURFACE CONTOURS
T2 AQUIFER
Summer 1970

Figure 21

QD7 101446NG: 101446.DTA 98-1633



LEGEND

Northern Adelaide Plains Proclaimed Region

Hundred boundary

Observation well and number — PTA 46

Potentiometric level (metres AHD) — -7.8

Potentiometric surface contours (metres AHD) — 10

0 5 10

KILOMETRES

Department for Water Resources

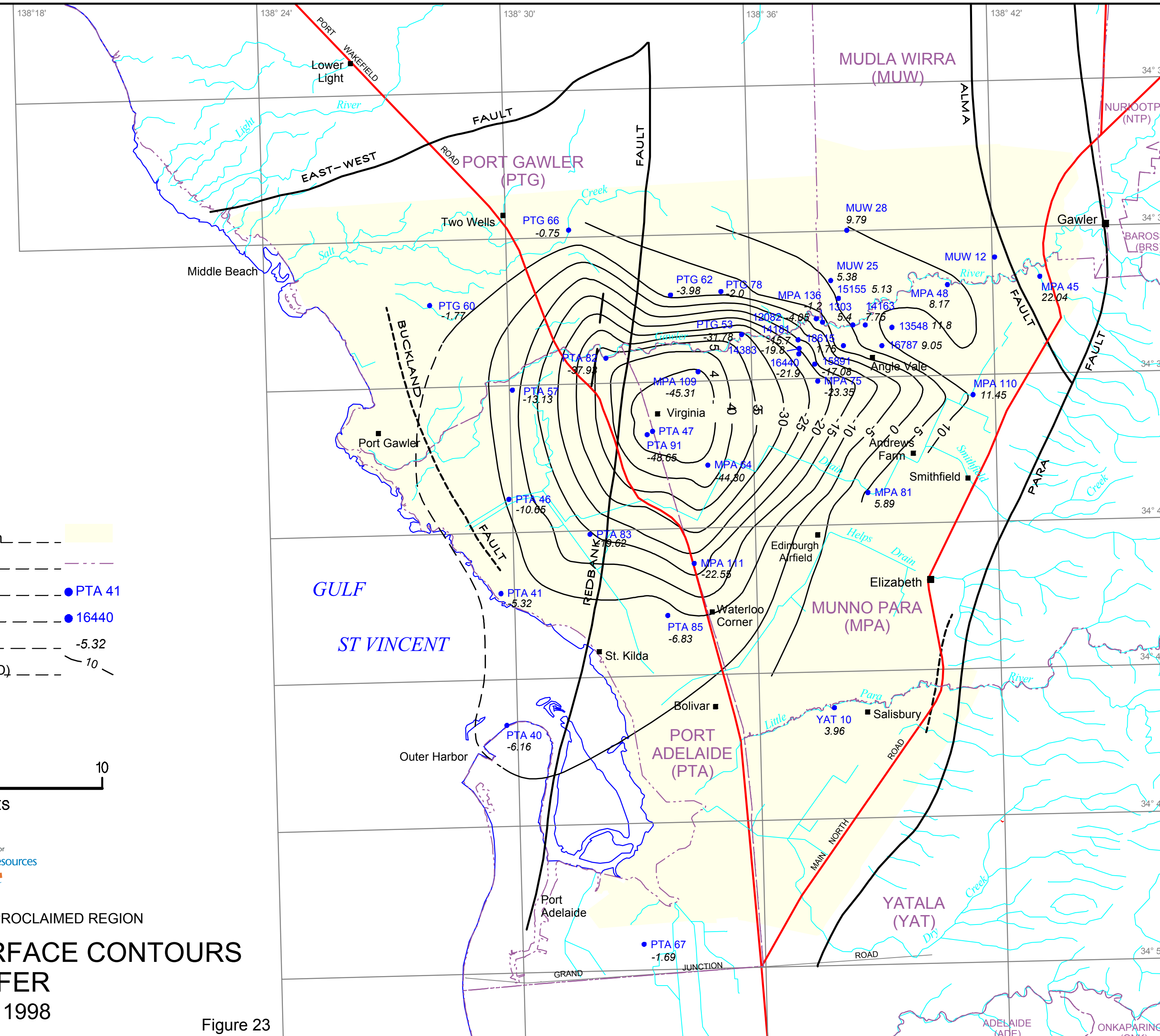
NORTHERN ADELAIDE PLAINS PROCLAIMED REGION

POTENTIOMETRIC SURFACE CONTOURS T2 AQUIFTER

March 1988

Figure 22

QD7 101446NG: 101446.DTA 98-1634



LEGEND

Northern Adelaide Plains Proclaimed Region

Hundred boundary

Observation well and number — PTA 41

Drillhole and number — 16440

Potentiometric level (metres AHD) — -5.32

Potentiometric surface contours (metres AHD) — 10

0 5 10
KILOMETRES

NORTHERN ADELAIDE PLAINS PROCLAIMED REGION

POTENTIOMETRIC SURFACE CONTOURS
T2 AQUIFER

March/April 1998

Figure 23

QD7 101446NG: 101446.DTA 98-1635

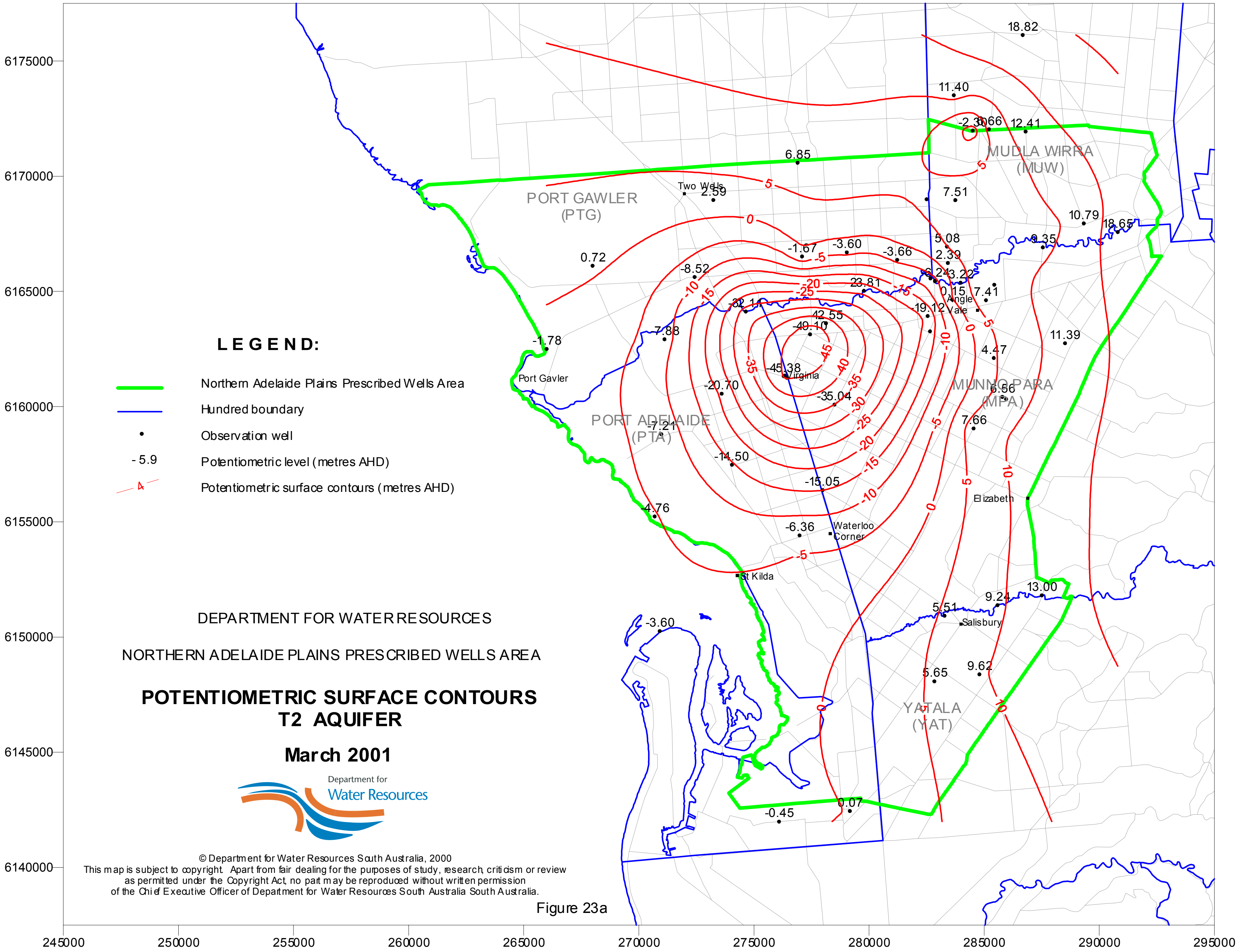
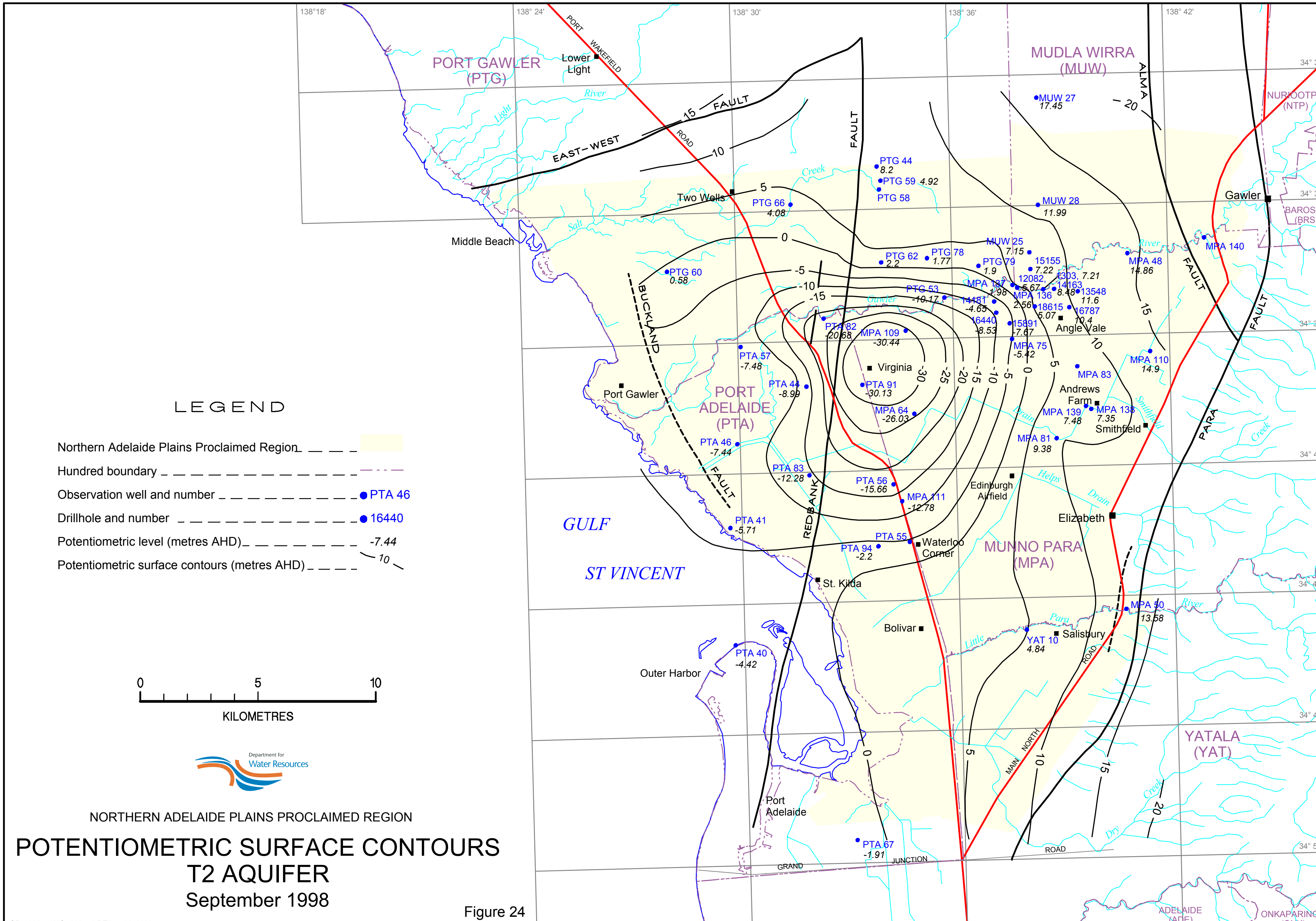

LEGEND:
Northern Adelaide Plains Prescribed Wells Area
Hundred boundary
Observation well
- 5.9 Potentiometric level (metres AHD)
Potentiometric surface contours (metres AHD)
DEPARTMENT FOR WATER RESOURCES
NORTHERN ADELAIDE PLAINS PRESCRIBED WELLS AREA
POTENTIOMETRIC SURFACE CONTOURS
T2 AQUIFER
March 2001
Department for Water Resources
PORT GAWLER (PTG)
PORT ADELAIDE (PTA)
MUDLA WIRRA (MUW)
MUNNO PARA (MPA)
YATALA (YAT)
Two Wells
Port Gawler
Virginia
Angle Vale
Elizabeth
Waterloo Corner
St Kilda
Salisbury
6175000
6170000
6165000
6160000
6155000
6150000
6145000
6140000
245000
250000
255000
260000
265000
270000
275000
280000
285000
290000
295000

Figure 23a



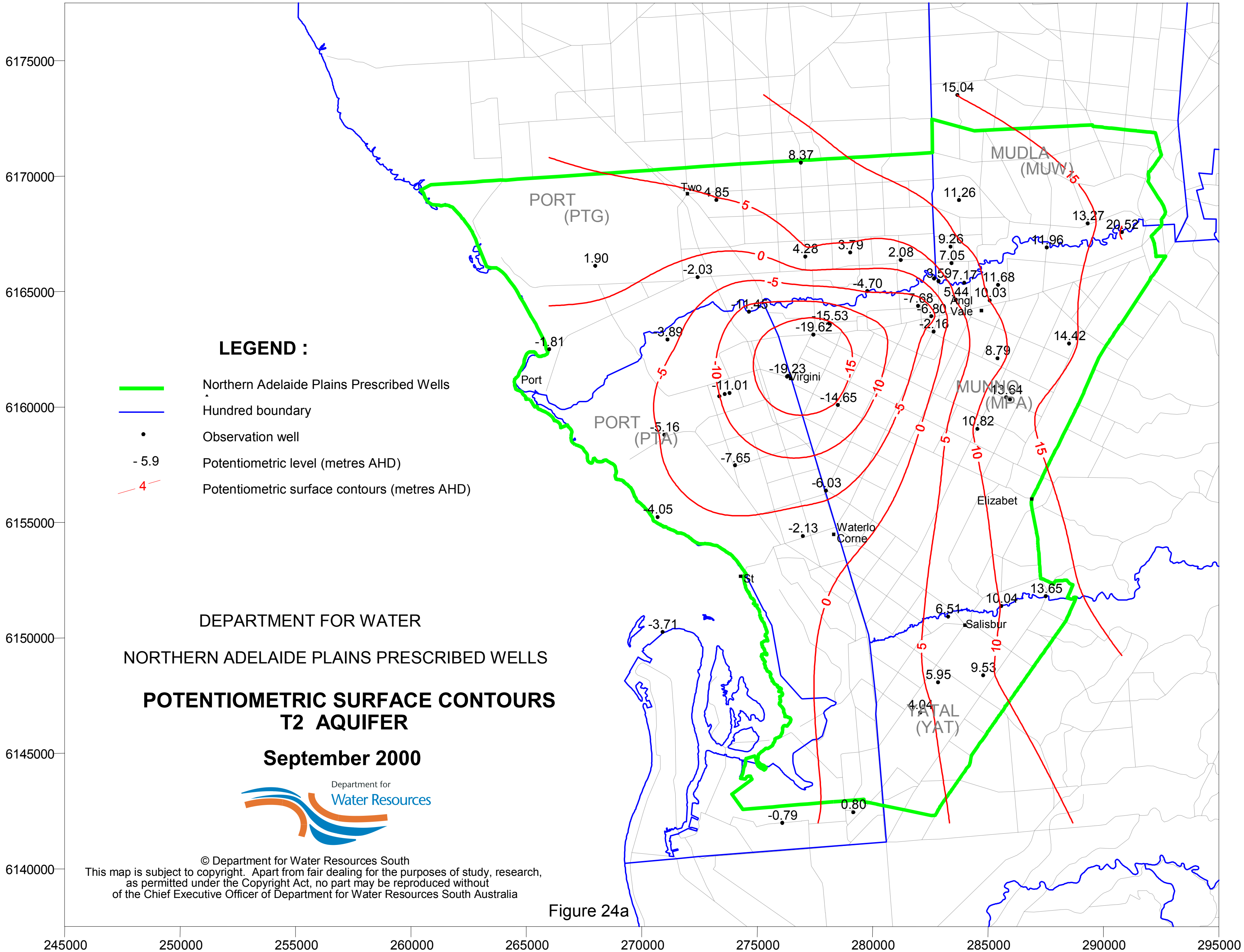
NORTHERN ADELAIDE PLAINS PROCLAIMED REGION

POTENTIOMETRIC SURFACE CONTOURS T2 AQUIFER

September 1998

Figure 24

QD7 101446NG: 101446.DTA 98-1636


LEGEND :
Northern Adelaide Plains Prescribed Wells
Hundred boundary
Observation well
- 5.9 Potentiometric level (metres AHD)
4 Potentiometric surface contours (metres AHD)
DEPARTMENT FOR WATER
NORTHERN ADELAIDE PLAINS PRESCRIBED WELLS
POTENTIOMETRIC SURFACE CONTOURS
T2 AQUIFER
September 2000
Department for
Water Resources
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PORT (PTG)
PORT (PTA)
MUDLA (MUW)
MUNNO (MPA)
YATAL (YAT)
Virgini
Elizabet
Waterlo Corne
Salisbur
Angl Vale
Two
Port
St
6175000
6170000
6165000
6160000
6155000
6150000
6145000
6140000
245000
250000
255000
260000
265000
270000
275000
280000
285000
290000
295000

Figure 24a

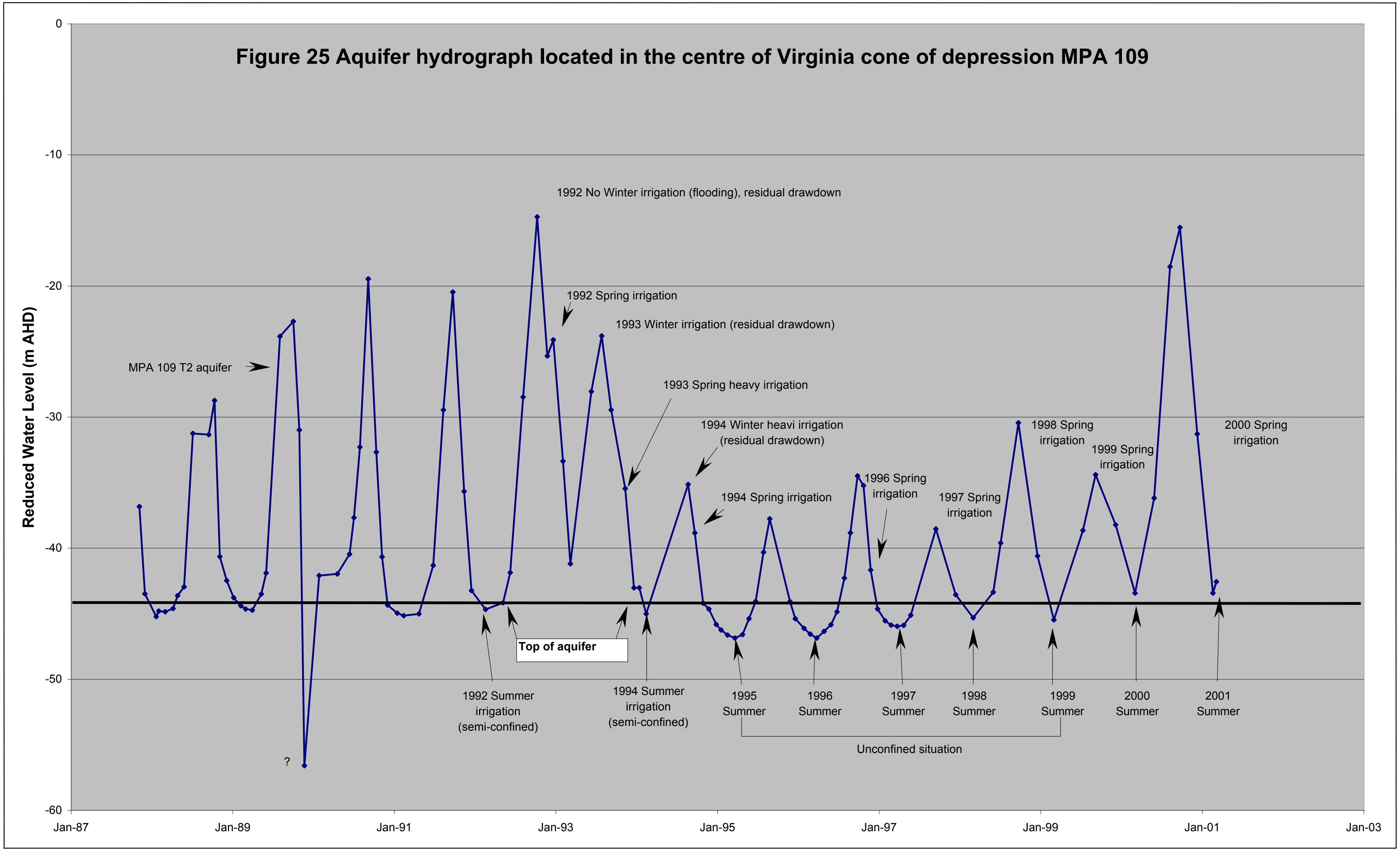

Figure 25 Aquifer hydrograph located in the centre of Virginia cone of depression MPA 109
Reduced Water Level (m AHD)
0
-10
-20
-30
-40
-50
-60
Jan-87
Jan-89
Jan-91
Jan-93
Jan-95
Jan-97
Jan-99
Jan-01
Jan-03
1992 No Winter irrigation (flooding), residual drawdown
1992 Spring irrigation
1993 Winter irrigation (residual drawdown)
MPA 109 T2 aquifer
1993 Spring heavy irrigation
1994 Winter heavi irrigation (residual drawdown)
1994 Spring irrigation
1996 Spring irrigation
1997 Spring irrigation
1998 Spring irrigation
1999 Spring irrigation
2000 Spring irrigation
Top of aquifer
1992 Summer irrigation (semi-confined)
1994 Summer irrigation (semi-confined)
1995 Summer
1996 Summer
1997 Summer
1998 Summer
1999 Summer
2000 Summer
2001 Summer
Unconfined situation
?

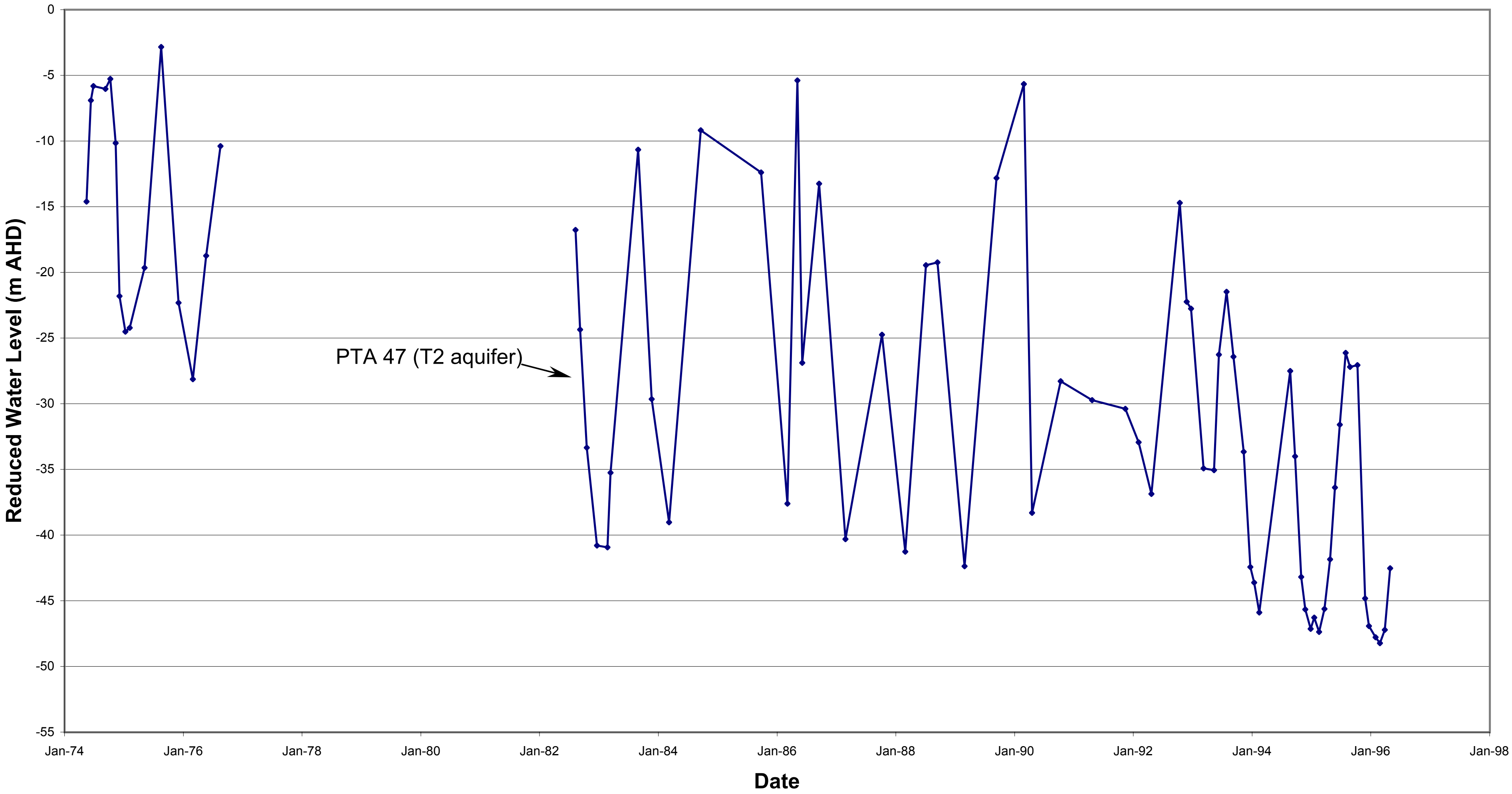

Figure 26 T2 Aquifer hydrograph located in the centre of Virginia cone of depression, Virginia Old Primary School MPA47 Hydrograph PTA 47 (T2-aquifer)

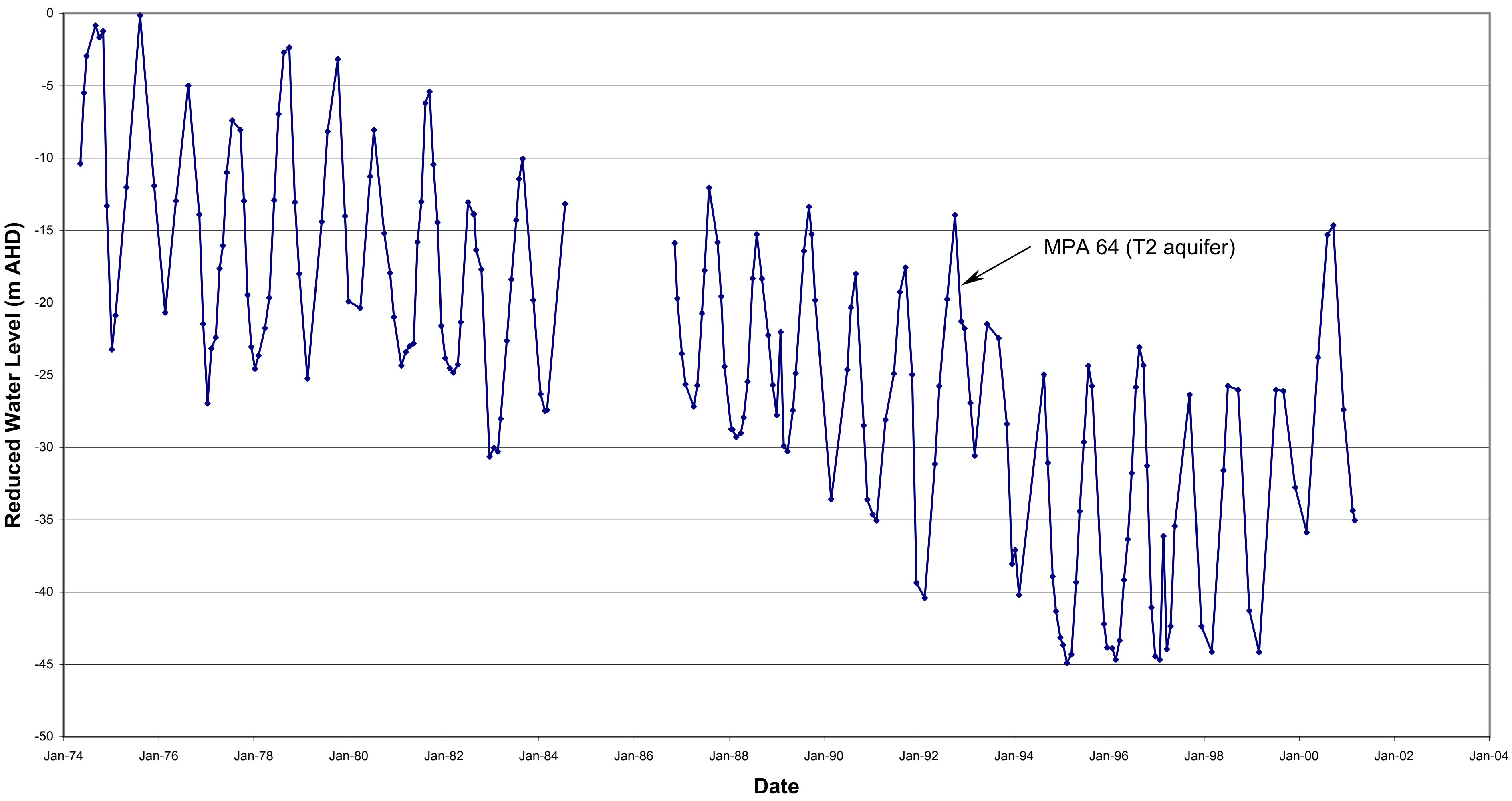

Figure 27 Hydrograph MPA 64 (T2-aquifer)

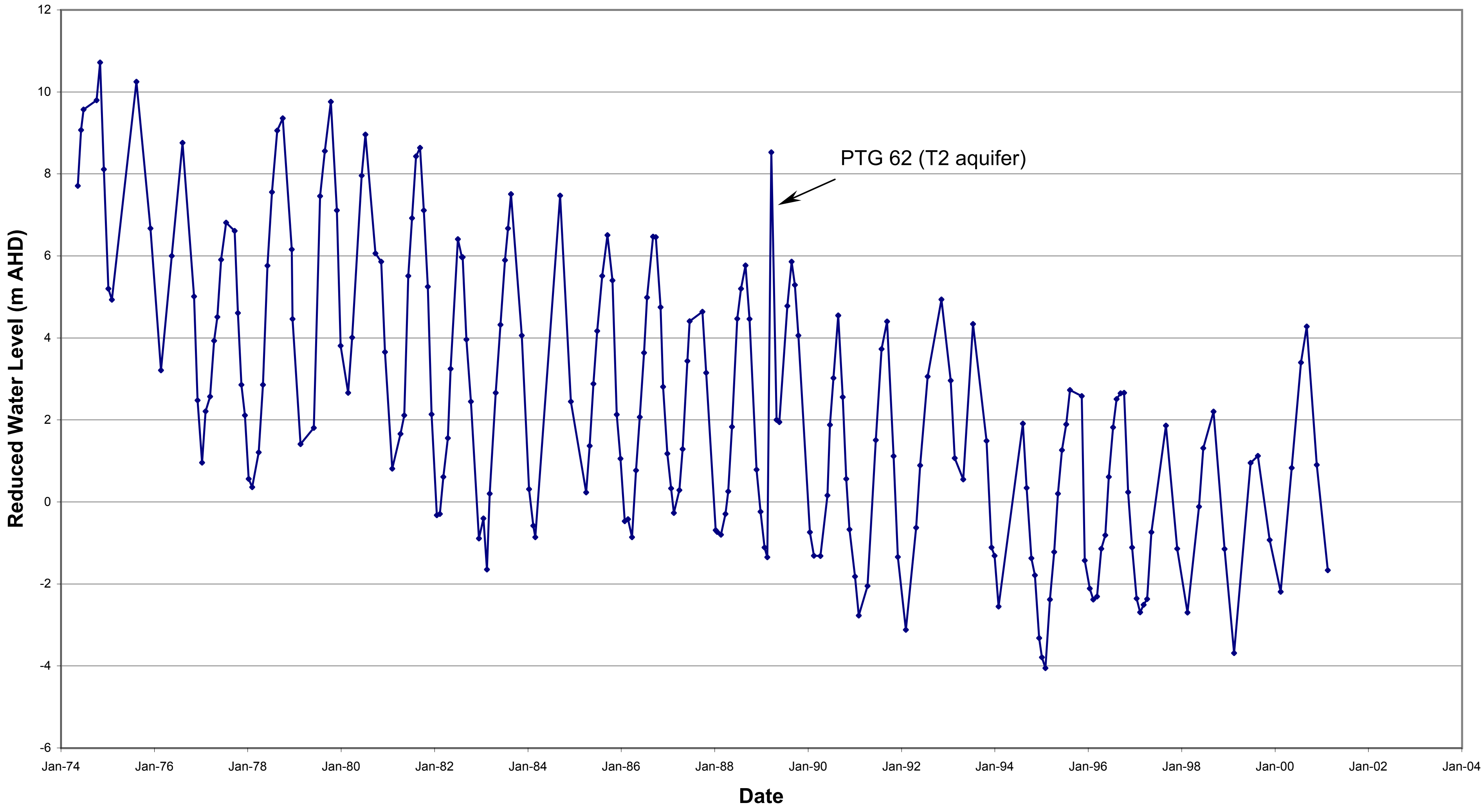

Figure 28 Hydrograph PTG 62

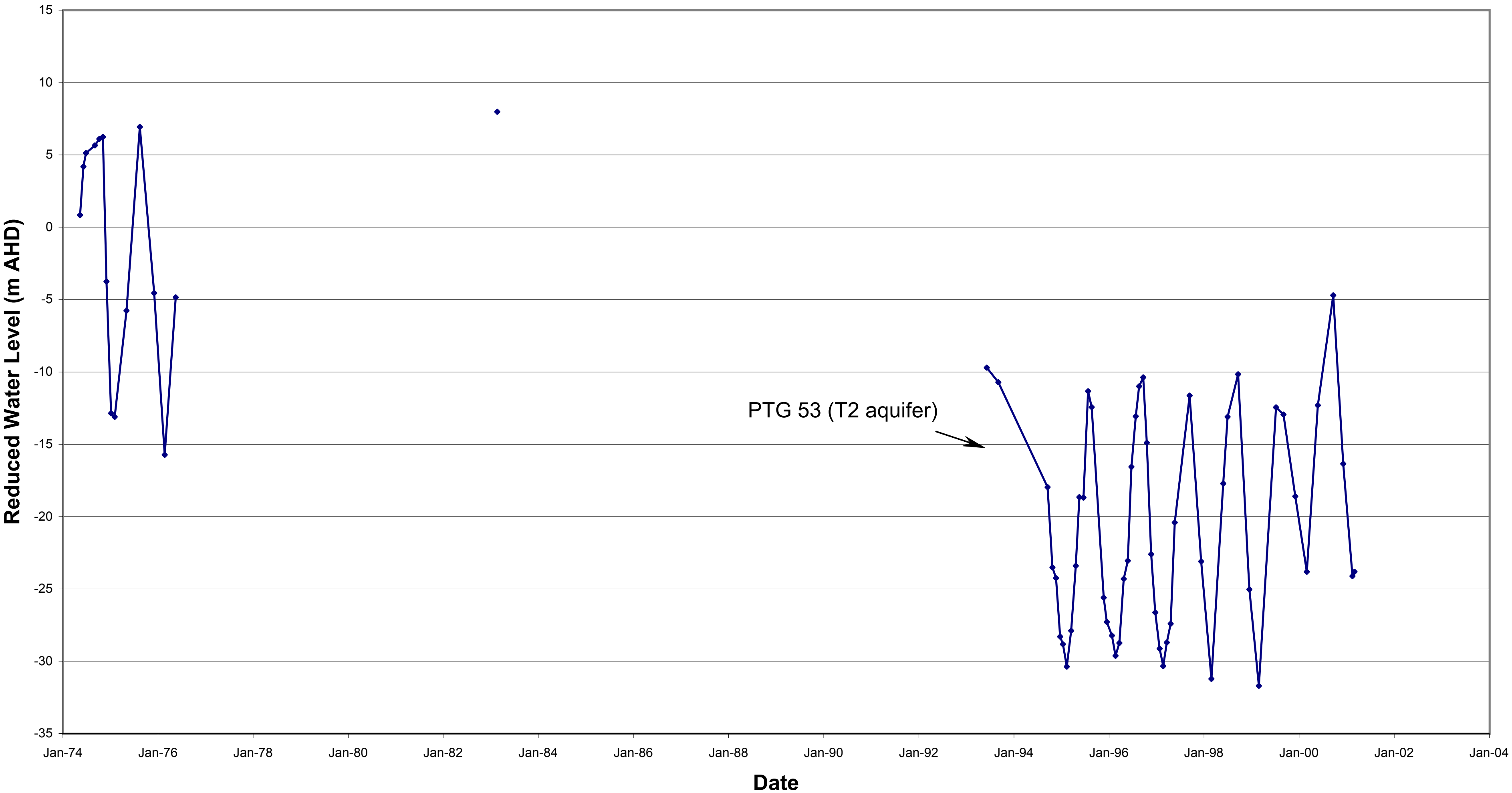

Figure 29 Hydrograph PTG 53 (T2-aquifer)

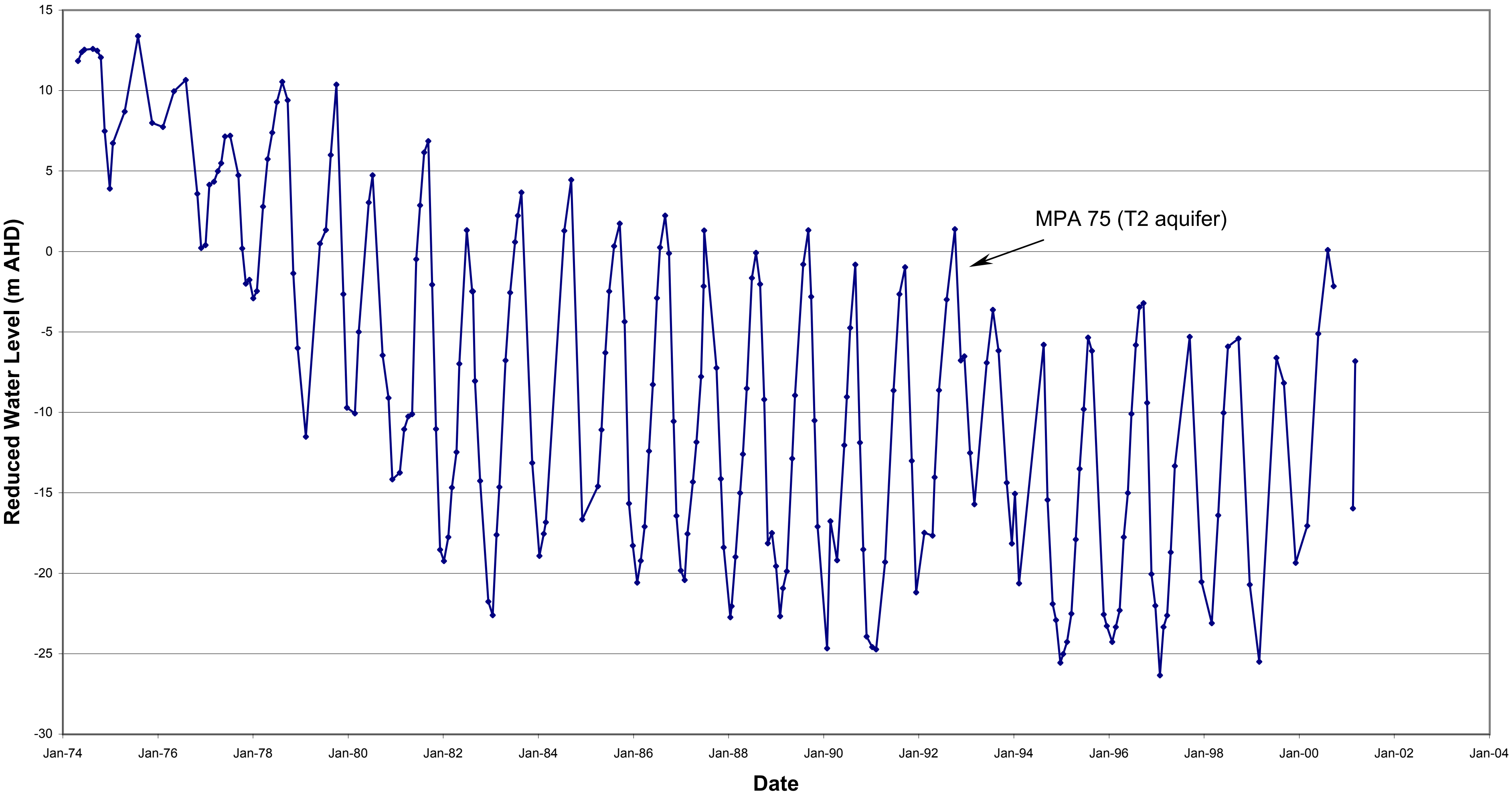

Figure 30 Hydrograph MPA 75 (T2-aquifer)

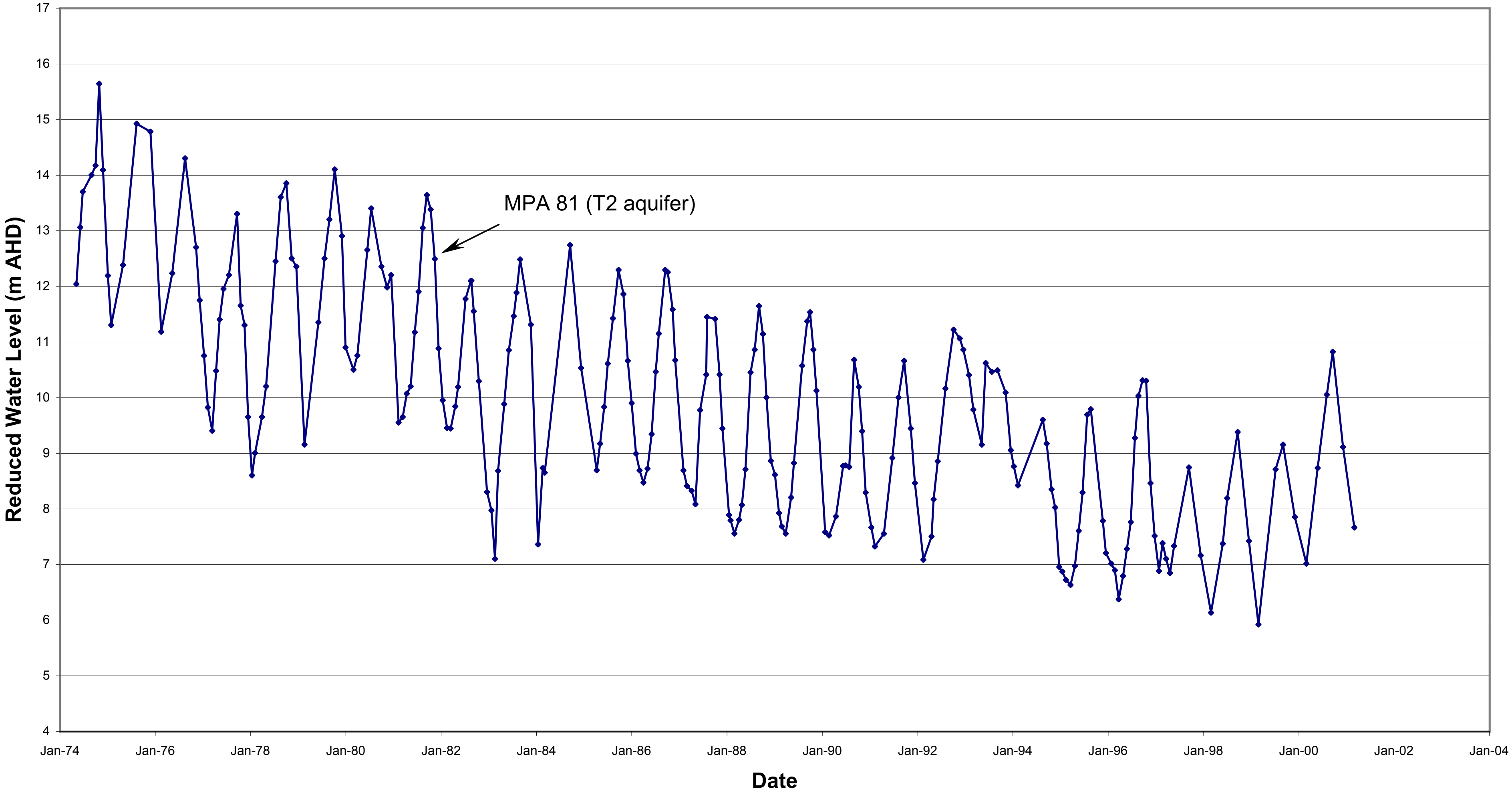

Figure 31 Hydrograph MPA 81 (T2-aquifer)

4.3.3.2 SALINITY DISTRIBUTION IN THE SECOND TERTIARY AQUIFER

Data collected from wells prior to the 1970s has been assumed to represent historic salinities within this aquifer. This data was used to construct a salinity map of the area (Fig. 32). Salinity distribution within the T2 aquifer shows low salinity groundwater of less than 700 mg/L occurring in two major regions — a northern region located in vicinity of the Gawler River and a small southern region surrounding the Little Para River.

In the Gawler River area salinity ranges from 700 mg/L to greater than 3000 mg/L (Fig. 18). Depth to the aquifer and groundwater salinity increases to the south, so that the aquifer is not utilised in areas south of Waterloo Corner.

It is important to note that in the Gawler River area, the areal extent of groundwater where salinity is less than 700 mg/L is much greater in the T2 aquifer than in T1 aquifer or any of the overlying Quaternary aquifers. This indicates a more complex recharge mechanism than the simple downward infiltration from surface drainage.

Salinities of more than 2500 mg/L are invariably located at the extreme edges of active recharge and flushing fronts.

There is evidence of salinity stratification within the second Tertiary aquifer, particularly south of Little Para River. It is unclear at this time if the salinity stratification occurs as a result of lower hydraulic conductivity zones across the facies variants or if there are thin semi-confining layers present.

4.3.3.3 VOLUME OF WATER STORED IN AQUIFER T2

The volume of water in storage in aquifer T2 is significant. For example, the area within the 1000 mg/L-salinity contour has been measured at 125 km^2. Within the area, the volume of water in elastic storage has been estimated at 1500 ML[†] : which is very small. However, the volume of water stored in the aquifer matrix, under the unconfined situation, is approximately equal to 1 250 000 ML[‡]. Theoretically, this is equivalent to 92 years of extraction at the current rate of 13 500 ML/yr, without considering the lateral through-flow. The total volume stored in the unconfined situation within the entire T2 aquifer will be many times greater.

However, due to several constraints, only a fraction of the 1 250 000 ML[§] (possibly 50%) is available for extraction. These constraints include leakage from saline aquifers, lateral movement of saline water from around the margins of the low salinity water, and reduced well yields and additional pumping costs as groundwater levels decline.

4.3.3.4 SEASONAL WATER LEVEL DECLINE AND FLUCTUATIONS

Selected hydrographs with relatively long-term records (Figs 25–31) show the seasonal fluctuations within the T2 aquifers and the overall decline during the period of record keeping.

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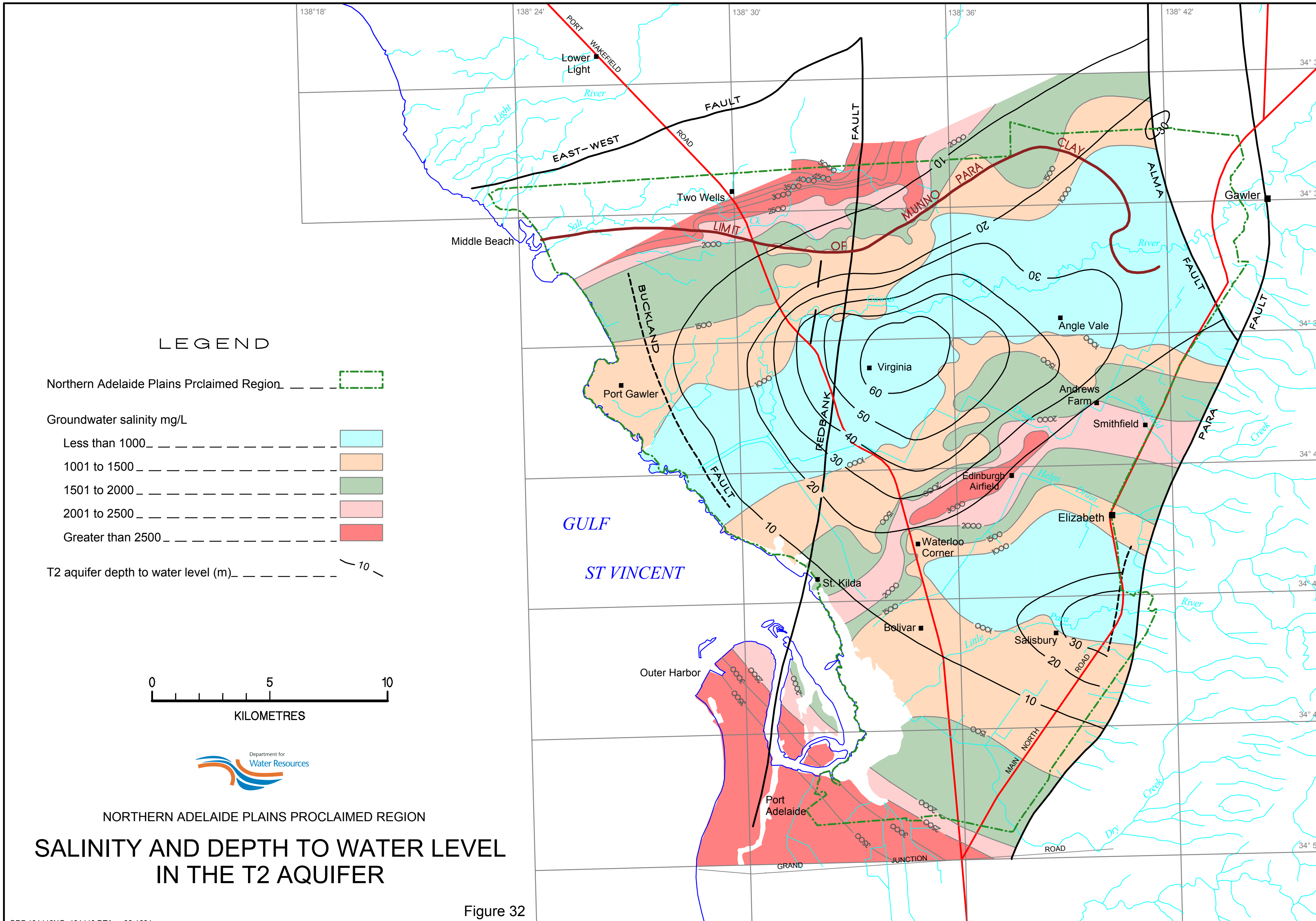
† *($V_e = h \times S \times A$, (where: h = hight of water column above top of the aquifer, S = storage coefficient and A = area) can be calculated to be ($60 (2 \times 10^{-4}) (125 \times 10^{+6})$*

‡ *($V_m = b \times sy \times A$, (where: b = thickness of the aquifer, sy = specific yield) is approximately equal to ($100 (1 \times 10^{-1}) (125 \times 10^{+6})$*

§ *($V_e = h \times S \times A$, (where: h = hight of water column above top of the aquifer, S = storage coefficient and A = area) can be calculated to be ($60 (2 \times 10^{-4}) (125 \times 10^{+6})$*



NORTHERN ADELAIDE PLAINS PROCLAIMED REGION

SALINITY AND DEPTH TO WATER LEVEL IN THE T2 AQUIFER

Figure 32

QD7 101446NG: 101446.DTA 98-1631

The rate of water level decline has been calculated at 0.35–0.7 m/yr, except in the centre of the cone. The most recent seasonal fluctuation measured varies between 7 m/yr in the centre of the cone and 20 m/yr outside the centre. The smaller seasonal fluctuation in the centre of the cone is related to the unconfined situation attained during summer pumping.

4.3.3.5 SALINITY INCREASES

Generally, the average water salinity in the T2 aquifer has increased by 200 mg/L during the last 30 years of pumping along some areas of the Gawler River. However, evidence suggests that in some areas negligible salinity increases have occurred.

The major reasons for salinity increases are:

- Point-source leakage from corroded casings. (Some leaky wells have recently been identified, some have been backfilled, while others have been recommended for remediation or backfilling.)
- Lateral flow from highly saline areas.
- Downward leakage of saline water occurring, due to the depressurising of the Tertiary aquifer (occurring in the fringe areas where the confining beds separating the Tertiary and Quaternary aquifers are either thin or non-existent).
- Aquifer interconnection following inappropriate well construction north of the Gawler River.
- Extensive pumping from the area inducing downward and/or upward leakage between Tertiary aquifers involving Munno Para Clay and/or Aldinga clay (not particularly significant at this stage of the investigation).
- Leakage via dual aquifer completion wells (i.e., wells completed in both T1 and T2 aquifers).

4.3.3.6 SECOND TERTIARY AQUIFER PARAMETERS

Aquifer parameters were determined from aquifer test data using the type curve matching (log–log) and the Jacobs straight-line (semi-logarithmic) methods. The most significant tests carried out in the Northern Adelaide Plain were at Andrews Farm, the Virginia Primary School and the proposed MFP site.

At the Andrews Farm site, an average transmisivity was calculated at 180 m^2/d with a storage coefficient of 1.9 to 5.6 x 10^{-4} and very low vertical hydraulic conductivity of the confining bed between the two Tertiary aquifers (Munno Para Clay). These low vertical permeability values suggest that the majority of flow to the well occurs as horizontal flow within the aquifer, with only a small contribution from vertical leakage.

Other tests suggest that transmissivity values range between 100–150 m^2/d with occasional values as high as 250 m^2/d. Overall, a transmissivity value of 80–125 m^2/d is considered representative.

4.3.4 Third Tertiary aquifer (T3)

This aquifer comprises the third intersected, saturated permeable Tertiary sediments, regardless of their stratigraphic age. The distribution of T3 is not well known but it is considered that it covers most of the NAP area as a thin, sandy layer with an average thickness of 5 m.

Few records relating to the T3 aquifer are available from drillholes in the Port Gawler, Virginia and Allenby Gardens areas. At the old Virginia Primary School site, the aquifer of Aldinga sands and Chinaman Gully sands was intersected at 215 m and the water level rose to an average 5 m above ground (PTA 88). This suggests a potential of upward leakage into the T2 aquifer under current potentiometric level conditions.

4.3.5 Fourth Tertiary aquifer (T4)

This aquifer comprises the fourth intersected, saturated permeable Tertiary sediments, regardless of their stratigraphic age.

The T4 aquifer area Consists mainly of South Maslin Sand (Unit 15) and occasional North Maslin Sand (Unit 17), is well distributed over the area and extends northward into the NAP.

Penrice Soda drilled two investigation production wells into the T4 aquifer, in the Dry Creek and Port Gawler areas, which indicated a potential supply of 20 L/s.

The two wells were completed as production wells in either the South Maslin Sand (Dry Creek Well) or in both the South and North Maslin Sands (Port Gawler Well). Preliminary results from both wells show that transmissivity ranges between 120–400 m^2/d.

In the Dry Creek Well 60 m of South Maslin Sand were intersected at 438 m. The salinity averaged 80 000 mg/L and water levels were 6–18 m above ground.

The Port Gawler Well intersected 17 m of South Maslin Sand 300 m below ground. Measured water levels were 2–5 m above ground and samples had a salinity of 55 000 mg/L. The anticipated yield is now 20–40 L/s.

Since this deep Tertiary aquifer contains high salinity water, little is known of its hydraulic properties. At Port Gawler, wells have intersected this aquifer at 254 m below ground, and water levels were 9 m above ground.

5.0 AQUIFER NATURAL RECHARGE MECHANISMS

5.1 HYDRAULIC CONTINUITY IN ST VINCENT BASIN

The lateral continuity of sediments and sedimentary rocks is important for fluid flow in sedimentary basins. This continuity can be impaired or enhanced by sudden changes in facies to a significantly low or highly permeable sediment. Several researchers have suggested that the localised faults act as conduits for fluids and that these might form important paths for lateral fluid flow from one aquifer to another.

Previous work (Gerges, 1999) has demonstrated hydraulic continuity between the NAP and Metropolitan areas. The size of the T2 aquifer cone of depression in the NAP is very small in comparison with the size of total St Vincent Basin aquifer. Consequently, pressure will propagate through the St Vincent Basin in response to any changes in stress.

The propagation of pressure is different from the actual movement of water molecules. Pressure propagation occurs almost instantaneously, while movement of water molecules can take considerably longer time frames involving days or thousands of years.

5.2 AQUIFER HISTORIC HEAD RELATIONSHIPS

Information from water cuts and early cable tool drilling has been used to assess pre-development aquifer relationships. Although the data is limited, and in some cases of dubious value, it suggests that deeper aquifers have a higher head than overlying aquifers.

Prior to significant groundwater development, most wells completed in the Tertiary aquifer were flowing, i.e., the potentiometric surface was approximately 10–15 m above ground, implying a historic upward hydraulic gradient. This process was at equilibrium for a long period of time, possibly several thousand years

This upward hydraulic gradient was also maintained for a considerable period of time and characteristic of the discharge side of a groundwater cycle. Upward flow (leakage) within the Quaternary sediments would have resulted in increasing salinity near the surface. Discharge from the system would have been either by evaporation (from Cb1) or flow from the shallower aquifers to streams and on to the Gulf.

This process may explain the gradual decrease in the area of the 1500 mg/L salinity zone from Q4 towards the Q1 aquifer. As better quality water leaks upward, evaporation concentrates the salt in the first Quaternary aquifer and/or the soil profile. This phenomenon can be seen in previously published salinity plans and sections (Gerges, 1997).

The present downward hydraulic gradient, maintained over the last 40–50 years of irrigation, will not have had the same effect on vertical salinity distributions as the historic upward hydraulic gradient that prevailed for several thousand years.

The historic artesian condition of T1 and T2 aquifers in these zones strongly suggests that upward leakage from T2 into T1, and from T1 into the overlying Quaternary aquifers, was an important component of the flow system. This means that, contrary to previous conclusions, infiltration of surface water along drainage lines does not recharge the first Tertiary aquifer.

There is limited knowledge of the boundary conditions at the western extreme of the St Vincent Basin. If the Tertiary aquifers are limited by an impermeable boundary, upward leakage represents the only natural discharge from the system.

The generally observed, historic, flat hydraulic gradient in the basin is due to the combination of relatively higher aquifer transmissivity and upward leakage to the Quaternary aquifers. In some areas west of the Para Fault and near surface drainage, some wells that show the Q2 aquifer head higher than Q1.

In the Little Para River area, the relatively steep hydraulic gradient area of 1.8 m/km is caused by the Carisbrook Sand, which constitutes up to 70% of the total aquifer thickness. This sand is known for its low to moderate hydraulic conductivity.

5.3 NATURAL RECHARGE MECHANISM

Previous investigations suggest that the predominant recharge sources for the area are the Gawler and Little Para Rivers. It is understood that during periods of flow, water percolates into the shallow Quaternary aquifers and then down into the confined Tertiary aquifers. River losses (Shepherd, 1975; p. 26) were calculated to be approximately 7410 ML annually (Gawler River 5010 ML/yr and Little Para River 2350 ML/yr).

Gerges (1999) concluded that most of the losses from river flows recharged the shallow Quaternary aquifer(s) and the balance infiltrated into the gravel river beds. This subsequently flowed horizontally as lateral flow through the gravel bed and ultimately discharged into the Gulf.

As demonstrated previously, and by Linke and Eberhard (1981), the historic water levels of the deep Quaternary aquifer and the Tertiary aquifer were above ground. In addition, later work by G.B. Allison and others stated that along the rivers, and before significant pumping, the potentiometric surface of the unconfined aquifer (presumably the Q1 aquifer) was lower than that of the confined system. This suggested upward hydraulic gradients, and hence the historic upward leakage from the Tertiary aquifer into the overlying Quaternary aquifer.

Recent investigations have revealed:

- Salinity profiles and distribution in all aquifers indicate that along both Rivers (except in very limited areas) the salinities of the Quaternary aquifers generally decrease with depth.
- Further salinity decreases occur in the underlying confined Tertiary aquifers T1 and T2.
- The areal extent and location of the 1000 mg/L salinity contour does not correlate with the same salinity zone in the overlying shallow Quaternary aquifer(s), suggesting that recharge to the Tertiary aquifers are more complex.
- The confining beds separating the Quaternary (Q1, Q2 and Q3) aquifers are of low vertical hydraulic conductivity, 10^{-5} to 10^{-6} m/d. (The vertical hydraulic conductivity of the confining beds separating aquifers T1 and T2 was tested at three locations (St Kilda, Virginia and near Angle Vale) and several other sites in the Adelaide Metropolitan area. They proved to be consistently low in the range 10^{-6} to 10^{-7} m/d.)
- Historically aquifer T2 has a higher head than aquifer T1, and both were artesian in certain areas prior to development.

Previous work on the T1 and T2 aquifers (Shepherd, 1975) suggested:

- negligible change in elastic storage
- no change in matrix storage
- annual recharge from surface drainage of 5500 ML/yr
- annual extraction from the Tertiary aquifer was mostly replenished by leakage from the overlying, highly saline Quaternary aquifer
- net leakage from the Quaternary aquifer to both T1 and T2 Tertiary aquifer was 17 950 ML/yr.

Based on these investigations, and assuming a negligible change in head, leakage into the Tertiary aquifers (the inflow) must be equal to extraction from the Tertiary aquifers (outflow).

Assuming that the annual extraction from the T2 aquifer only over the last 30 years is constant at 13 500 ML/yr, and is replenished by leakage, the total volume of groundwater extracted from the T2 aquifer over the last 30 years has been 405 000 ML (4.05×10^{11} L). The average salinity of extracted water from T2 aquifer is 1000 mg/L. The total amount of salt extracted from the T2 aquifer over the last 30 years can therefore be calculated at 4.05×10^{5} t*.

Previous work in 1975 concluded that outflow from the Tertiary aquifer was replenished by net leakage from the overlying Quaternary aquifer which had an average salinity of 3000 mg/L. Therefore, the amount of salt introduced into the Tertiary aquifer over 30 years can be calculated at 1.215×10^{6} t†.

A comparison of the salt inflow value of 4.05×10^{5} t with the salt outflow value of 1.215×10^{6} t indicates that a net value of 8.1×10^{5} t (8.1×10^{14} mg/L) of salt has been introduced into the Tertiary aquifers. The anticipated salinity of groundwater from the T2 aquifer over the last 30 years can therefore be calculated at approximately 2000 mg/L‡.

On this basis, irrigators should have experienced considerable increases in groundwater salinity particularly in the centre of the cone where the maximum leakage occurs. However regular sampling in the last 10–12 years from properly constructed wells, and salinity results from recently constructed wells in the centre of the cone, show a salinity of 600–800 mg/L which is at odds with the anticipated figure of 2000 mg/L**.

It is consequently suggested that water released from storage has been mostly replenished by lateral through-flow from low groundwater salinity preferential flow corridors located along existing low salinity zones including an area under the Gulf of St Vincent.

All of these observations also suggest that historic recharge to the deeper Quaternary aquifers, and to aquifers T1 and T2, did not occur as a result of downward leakage from the shallow Quaternary aquifers as concluded previously.

The prime source of recharge to the Tertiary aquifers is considered to be from the rainfall-fed fractured rock bedrock aquifers in the Adelaide Hills (Gerges, 1987, 1999). Since water levels in the Hills are at a higher elevation of water levels, these bedrock aquifers act as a source of pressurised water to the less elevated Tertiary aquifers within the NAP. The conceptual model of the area (Figs 2 and 2a) indicates that lateral flow occurs via preferential flow paths through the fractured rock aquifer into the Tertiary aquifers, and should theoretically equal the safe yield of the Tertiary aquifers. The recharge from the fractured rock aquifer is equal to lateral flow through the Tertiary aquifers. The volume of recharge from the fractured rock aquifer in the Hills is likely to vary as the hydraulic gradient in the Tertiary aquifers system changes.

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* *13 500 ML/yr x 30 yr = 4.05×10^{5} ML = 4.05×10^{11} L amount of salt from outflow at 1000 mg/L = $((4.05 \times 10^{11})(1000)) / 10^{9}$ = 4.0510^{5} t.)*

† *13 500 ML/yr x 30 yr = 4.05×10^{5} ML = 4.05×10^{11} L amount of salt from outflow at 3000 mg/L = $((4.05 \times 10^{11})(3000)) / 10^{9}$ = 1.21510^{6} t).*

‡ *Anticipated salinity increases in T2 aquifer over 30 yr (mg/L) = salinity increases over the 30 yr (8.1×10^{14}) / volume extracted from T2 aquifer over 30 yr (4.05×10^{11}) = 2000 mg/L.*

** *Anticipated salinity increases in T2 aquifer over 30 yr (mg/L) = salinity increases over the 30 yr (8.1×10^{14}) / volume extracted from T2 aquifer over 30 yr (4.05×10^{11}) = 2000 mg/L.*

Discharge from the Tertiary aquifers at the western boundary must occur from a major structure in the Gulf, or by upward leakage to the overlying aquifers at the boundary. Under a non-stressed condition, discharge should equal the natural through-flow. An alternative conceptual model has been developed recently suggesting that fresh water in the deep Tertiary aquifers may have been initially stagnant, and formed during the subsidence of the basin, prior to the deposition of Quaternary sediments.

The lowest salinity in the area is recorded along a corridor surrounding and in proximity of Gawler and Little Para Rivers. The extent of this lowest salinity corridor is into the north and up-gradient of the Gawler River. It is inferred that this corridor may represent an ancient narrow buried river channel, formed during the Tertiary period (ancestor to present day rivers), flowing toward the west and southwest and discharging into Gulf St Vincent.

The low salinity groundwater found in the sediments up-gradient of the Gawler River and away from the Little Para River (in the Waterloo Corner area) support the revised recharge mechanism. Consequently, it is considered that contributions of the rivers to the recharge of the deep Tertiary aquifers is negligible.

Most irrigation now takes place from the Tertiary formation in this corridor, which is a zone of high permeability and active lateral through-flow.

6.0 SUSTAINABLE YIELD

The concept of sustainable yield still receives much debate, but it is currently defined in the State Water Plan 2000 as; *“the groundwater extraction regime, measured over a specified planning timeframe, that allows acceptable levels of stress and protects the higher value uses that have a dependency on the water”*.

The extraction of groundwater from a basin can be expected to cause some impact on the quantity or quality of the groundwater. This is acceptable provided that the impacts are ‘reasonable’ and do not constrain the opportunity for future generations to enjoy the use of the resource.

7.0 STATUS OF THE BASIN

Analysis of basin status is based on information up to 1999. The two major problems facing present day groundwater users in the NAP are water level decline and salinity increases.

7.1 WATER LEVEL DECLINE AND CONE OF DEPRESSION

The decline in water level and the development of the cone of depression, are in response to:

- Intensive pumping from the major aquifers, resulting in the development of a steep cone of depression during summer, which does not recover completely during winter.
- A concentration of pumping wells in a small area, causing well interference.
- A relatively small lateral flow.
- Pumping during winter.
- The effect of a cumulative residual drawdown over a number of years of pumping, which shows as a continuous decline in water level.

- The imbalance between the short duration of the recovery period and the pumping period.

In T1 aquifer, water level has declined by 10–30 m in the centre of the area. The present day potentiometric surface is severely modified by present day pumping, and shows steep cones of depression in the Waterloo Corner and the Penrice Soda areas. The permanent cone in the Penrice Soda area evolved during the mid 1950s as a result of the heavy continuous industrial pumping and seasonal irrigation pumping elsewhere. The seasonal cone at Waterloo Corner developed in the early 1990s as the result of intensive irrigation.

The T2 aquifer water level in the area has declined over the last 40–50 years by approximately 50–70 m (-45 to -50 m AHD) in the centre of the irrigation area. During summer (Figs 25 and 26) the water level is several meters below the top of the aquifer (unconfined situations). This recovers during winter to approximately 5–10 m above the top of the aquifer (semi-confined situation).

It is anticipated that a minor decline of water levels will occur centred around the area where the greatest concentration of extraction is located. As the cone progressively expands, the unconfined situation may also spread laterally, covering a larger portion of the irrigated area. Under the current extraction regime it is also expected that areas outside the centre of the cone will continue to show declining groundwater levels (Figs 28 and 31) and that there will be a noticeable lateral expansion of the cone.

The observation well MPA 109 (located almost in the centre of the T2 aquifer cone of depression; Fig. 25) shows water level during recent winters is averaging 5 m above the aquifer. This suggests a massive loss in elastic storage and rapid decline of water levels to the unconfined situation, primarily due to intensive pumping during winter months. Two observations and events support this conclusion:

- The shift of the centre of the cone from around observation well PTA 47 during summer (Fig. 23) to the vicinity of observation well MPA 109 during winter (Fig. 24). This suggests a shift in the location of the winter pumping centre.
- During winter 1992, heavy rain and flooding resulted in a temporary halting of winter irrigation, which in turn resulted in a 5 m recovery of water levels compared to the previous years (Fig. 25). The spring 1992 residual drawdown (Fig. 25) was approximately 12 m higher than that of 1991.

However, when the spring 1992 residual drawdown is compared with those of spring 1995–98, there is a significant decline in water levels as a result of winter irrigation. It also suggests significant increases in the volume of groundwater extracted in the last five years, particularly from the T2 aquifers during winter. This clearly demonstrates the effects of winter residual drawdown on water levels for the following summer extraction period. Higher winter water levels mean higher water levels at the start of the heavy summer extraction, and consequently less drawdown during summer months. It also indicates the importance of recovery periods during winter months.

7.2 SALINITY INCREASES

Average water salinity has increased in some areas by 200 mg/L during the last 30 years of pumping along the Gawler River in the T2 aquifer. Salinity in the T1 aquifer near Waterloo Corner has increased up to 800 mg/L and occasionally to 6000 mg/L.

Although salinity increases have been highlighted as a major threat to the basin, native groundwater remains almost unchanged in a large number of wells.

The major reasons for salinity increases in T1 aquifer are:

- Leakage via corroded well casings (point source).
- In Waterloo Corner – St Kilda areas, groundwater salinity levels in T1 aquifer are highly sensitive to pumping; high pumping will accelerate downward leakage of saline water from overlying Quaternary aquifers, including Q4 aquifer. This largely depends on the thickness, distribution and consistency of the confining bed separating T1 aquifer from Q4 aquifer and shallow saline Quaternary aquifers from Q4 aquifer.
- Sensitivity of salinity levels in the T1 aquifer at the Waterloo Corner and St Kilda areas to pumping, which, in these areas, will accelerate downward leakage of saline water from overlying Quaternary aquifers including the Q4 aquifer.
- Lateral flow from highly saline area.
- Leakage occurs via dual aquifer completion wells (i.e., wells completed in both aquifers T1 and T2).

The major reasons for salinity increases in T2 aquifer are:

- Leakage via corroded well casings (point source).
- Downward leakage occurs on the fringes of the area (where there are thin, or no confining beds, separating the Tertiary aquifers from the Quaternary aquifers) as a result of depressurising the Tertiary aquifer (mainly T2 aquifer several kilometres north of Gawler River).
- Lateral flow from highly saline area.
- Leakage via dual aquifer completion wells completed in both T1 and T2.

7.2.1 Salinity increases in T1 or T2 as result of leaky wells

Many irrigators are experiencing problems with increasing groundwater salinity in wells, while others face such problems in the future. Salinity increases in wells can be sudden, due to abrupt casing failure, or gradual as the casing corrodes slowly and the number and size of the corroded holes increases. Gradual increases in salinity can also be due to regional salinity changes in the aquifer caused by over pumping

With leaky wells, holes in the casing allow the saline groundwater to flow into the well. In some cases, spaces exist between the well casing and the soil formation, allowing saline water to move downward through these annular spaces into the production aquifer. These problems occur mainly in older wells with un-cemented casing, however, they can also occur in newer, poorly constructed wells.

Since there is a slow rate of groundwater movement, the effect of a leaky well on nearby wells often remains unnoticed, until the wells actually begin to produce saline water. By that time a significant volume of saline water may have leaked into the main irrigation aquifer and a large area of the aquifer could have been affected, with a ‘plume’ of salty water moving in the direction of groundwater flow.

Calculating the anticipated amount of leakage from a corroded casing is based on the assumption that leakage from a shallow saline Quaternary aquifer(s) ranges between 0.1–1 L/s per well. If leakage has occurred over the last 20 years, the leakage per well is calculated at between 63.7–637 ML (3.18–31.8 ML/yr). Locally, these volumes will form a large bubble of contaminated water, which will enter the aquifer at between 5–30 m per year (more likely about 10 m) depending on its location in relation to a cone of depression.

Based on the assumption that between 200 and 500 wells are leaking within the area at the lowest rate of 0.1 L/s, total leakage is between 636 ML/yr (200 wells) and 1590 ML/yr (500 wells). This represents a large volume of saline water that is added annually into aquifer storage. It also suggests that water levels monitored in leaky wells provided inaccurate measurements. This has been noticed in rehabilitated observation wells.

Experience with the recovery of storm water injected into aquifers (a similar scenario to saline water from a leaky well) suggests that once the saline plume has developed and established, it is difficult to revoke it and revert the aquifer groundwater to its natural salinity. In some instance prolonged, steady and continuous pumping out, proved useful in restoring natural groundwater salinities. The duration of rehabilitation extraction depends on several factors including; aquifer parameters, the size of the contaminated plume and the duration of the leakage of saline water. This method of aquifer rehabilitation is not recommended in cases where confining beds are collapsed as in some situations in the Waterloo Corner area.

Wells with corroded casing must be rehabilitated or backfilled with cement slurry by a licensed well driller before the groundwater becomes too saline for rehabilitation and possible further use.

8.0 PRELIMINARY QUALITATIVE WATER BALANCE OF T2 AQUIFER[††]

The water balance of T2 aquifer can be represented as:
Change in Storage = Inflow – Outflow.
Where Inflow = Lateral through-flow + vertical leakage + leakage via corroded casing.
Where Outflow = Pumping from the aquifer + vertical leakage + lateral outflow.

8.1 INFLOW

Based on the current summer potentiometric surface and an upper limit of aquifer transmissivity of 200 m^2/d, the tentative lateral through-flow in T2 was calculated at approximately 12 570 ML/yr, based on the following:

Lateral flow from east–northeast (from Adelaide hills)	~2930 M/L/yr (less than 1000 mg/L salinity corridor)
Lateral flow from west–southwest (from under St Vincent Gulf)	~1080 M/L/yr (less than 1000 mg/L salinity corridor)
Lateral flow from north–northwest	~3925 M/L/yr (more than 1000 mg/L salinity corridor)
Lateral flow from south–southeast (from under St Vincent Gulf)	~4630 M/L/yr (more than 1000 mg/L salinity corridor)

[††] *Not to be used for quantitative assessments*

Downward leakage from T1 aquifer into T2 aquifer was calculated at approximately 400 ML/yr (using the conservative vertical hydraulic conductivity of Munno Para Clay).

Allson, et al., (1973; p. 499) states that the Quaternary aquifers recharge to the Tertiary aquifers is $0.43 \pm 0.1 \times 10^6\ m^3/yr$ (430 ML/yr); a value similar to the approximate leakage through Munno Para Clay.

A possible additional source of inflow into the aquifer is from leaky wells. The majority of production wells in the NAP are completed in the T2 aquifer, and most of the leakage from corroded wells occurs into this aquifer. An accurate induced volume is therefore difficult to determine, however, it is thought to vary significantly with a minimum leakage of 630 ML/yr.

Total estimated annual inflow into the T2 aquifer is ~13 600 ML.

8.2 OUTFLOW

Average annual pumping from T2 aquifer has been estimated at 13 500 ML and lateral outflow from this aquifer, including outflow due to leakages, are almost negligible. Change in storage from the T2 aquifer area was calculated at ~100 ML/yr.

8.3 WATER BALANCE

The preliminary water balance (Gerges, 1999) for the area can be calculated as:

$$\Delta s = (12\,570 + 400 + 630) - 13\,500$$

This compares to the calculated change in storage (**Δs**) of approximately 100 ML/yr. Minor imbalances represent small inaccuracies in the measurements of aquifer transmissivity, confining bed vertical hydraulic conductivity and extraction rates from the aquifer. However inaccuracies could also be due to upward leakage from the T3 aquifer that has not been accounted for. Alternatively, they may represent variations in the inflow volumes from leaky wells.

The lateral through-flow mostly represents the natural recharge to the aquifer and it is considered that increasing or decreasing the gradient of the potentiometric surface will result in corresponding increases or decreases in lateral through-flow. Consequently, natural lateral through-flow prior to European settlement (when gentle, potentiometric surface gradients prevailed) was considerably less than at present.

Increasing extractions from the area will slightly enhance lateral through-flow but could also cause further undesirable outcomes, including leakage from overlying and/or underlying saline aquifers, and accelerated lateral movement of saline fronts into pumping centres. In addition, lowering water levels in pumping aquifer(s) could result in higher pumping cost.

9.0 AQUIFER STORAGE AND RECOVERY IN NAP AREA

Gerges (1992, 1994, 1996, 1999) has proposed aquifer storage and recovery (ASR) as a solution for the problems in the NAP area, including storing storm water, winter runoff from the rivers and/or storing up to 9000 ML of treated effluent from the Bolivar treatment works in the second underlying Tertiary aquifer.

Preliminary numerical modelling indicates that injection and subsequent extraction is hydrogeologically acceptable and will have other benefits for the groundwater system.

A fundamental assumption is that wastewater used for injection into aquifers must receive an adequate degree of treatment prior to injection, which will minimise impact on the natural groundwater and the need for further treatment of the recovered water before re-use.

In the NAP area several solutions for declining water levels have been proposed, including the re-use of effluent for direct irrigation and the winter storage of surplus water in the major Tertiary aquifers, using ASR methods.

Several aquifer storage options were examined (Gerges, 1996), including the preferred option of using 80% (120 ML/d) of the treated effluent for direct irrigation and injecting the remaining 20% into the aquifer system for storage. The concept of injecting 9000 ML of reclaimed water into the Tertiary aquifers was reported by Gerges in 1996.

The benefits of adopting ASR options in NAP area include:

- Storing the Bolivar-treated effluent within the elastic storage of the T2 aquifer that will transmit the pressure throughout the area of the cone of depression almost instantaneously.
- Increasing the potential holding capacity for injected water by using the deep water levels within the cone of depression.
- Transmitting the pressure to achieve substantial savings with the pipeline layout, which only needs to carry water into the cone of depression rather than to every irrigator.
- Reducing the need for additional infrastructure on farmland, such as dams, pumps, valves, etc.
- Reducing evaporation from farm dams.
- Retaining the existing infrastructure (such as extraction wells) on farmlands, some of which can be converted into injection/extraction wells.
- Removing the stigma attached to using Bolivar effluent for irrigating market garden vegetables, particularly for the overseas market.
- Reducing the risk of re-infecting effluent water by storage in farm dams where the high nutrient content of the water can suit blue-green algal blooms, etc.

The required amount of injection to keep the basin at a sustainable level is far less than the amount of treated effluent generated at Bolivar. In this case, a net saving of Bolivar treated effluent will be piped, injected and stored; creating low salinity bodies in new areas with good soils, but poor quality natural groundwater.

It is apparent that a reduction in total extraction (due to irrigation directly from the Bolivar–Virginia pipeline) from the area, and/or ASR implementation, could result in an elevation of the T2 aquifer water levels to a level equal to or higher than the overlying aquifers. This will benefit the area in several ways:

- Decrease salinisation of the T2 aquifer by reducing downward leakage from overlying saline aquifers via corroded well casings. It will also reduce upward leakage from the underlying saline T3 aquifer, which has a head ~55 m above the T2 aquifer head in the centre of the cone of depression.

- Reduce lateral flow from the saline aquifer margins.
- Increase pressure, which is transmitted almost instantaneously over a large area while the injected water remains in the vicinity of the injection well for extraction. This is particularly useful where the natural groundwater is highly saline. The presence of the confining layer (Munno Para Clay) over the majority of the area will significantly reduce upward leakage to overlying aquifers.

Appropriate spacing of injection wells reduces interference and maintains a constant injection rate. A potential risk that may arise from ASR is that if increases in aquifer pressure are excessive it may re-activate abandoned and/or leaky wells if the aquifer becomes artesian.

10.0 SUMMARY AND CONCLUSION

10.1 WATER LEVEL TRENDS

Heavy extraction occurs from this area, resulting in a high well interference, depletion of elastic storage and the development of a pronounced cone of depression during summer. This cone of depression does not recover completely during winter. It is a result of the inability of the aquifer to transmit water into its centre, where a high concentration of pumping wells operate extracting a large volume of groundwater.

It is evident that during the last 40–50 years the area has suffered a massive reduction in pressure, and consequently water levels have declined by 70–75 m in the centre of the cone.

The most recent seasonal measured fluctuation varied between 7 m/yr (MPA 109, Fig. 25) in the centre of the cone to 20 m/yr (MPA 75, Fig. 30) away from the centre. The smaller seasonal fluctuation in the centre of the cone is related to an unconfined situation attained during summer pumping and winter irrigation pumping.

At present, during summer in the Virginia area, the cone of depression reaches the top of the aquifer which becomes locally unconfined. It is expected that a minor decline of water levels will occur in the centre of the area and the major decline may continue outside the centre of the cone. As the cone progressively expands, the unconfined situation may spread laterally covering a larger portion of the irrigation area.

There are numerous examples of confined aquifer systems that have fully recovered following the cessation of winter pumping, or a significant reduction in total extraction. An example of winter recovery occurs within the West Lakes Golf Course area: summer extraction produces a cone of depression up to 30 m deep, which recovers almost completely during winter.

The Angas–Bremer Proclaimed Area is a classic example of a re-pressured aquifer reacting to a significant reduction in extraction. In this area, the aquifer has reduced from 24 000 to 5000 ML/yr over the last few years. However restoring groundwater salinity to its natural level will require a longer period of time.

In Israel, the aquifer that underlies Tel Aviv was used to such an extent that sea intrusion occurred. Recent reductions in extractions, together with ASR applications, have raised water levels significantly.

These examples demonstrate the rapid recovery of the potentiometric surface of a confined aquifer resulting from reduced stress and pressure transmission — rather than the physical movement of water.

Generally, the development of the cone of depression and decline in water is in response to:

- Intensive pumping within a localised area causing the development of a steep cone of depression during summer, which does not recover completely during winter.
- The low level of natural replenishment to the aquifer system.
- Pumping during winter for industrial and/or irrigation purposes.
- The short duration of the recovery period in relation to the pumping period.

Extraction during summer from pumping centres with high concentrations of wells in small areas results in significant interference between wells and an excessive drawdown.

10.2 SALINITY TRENDS

A major concern for the area is the increase in salinity, from leakage occurring from corroded well casings and poorly cemented wells, induced leakage from the overlying aquifers, and (to a lesser extent) from lateral flow from surrounding highly saline areas.

Despite the presence of the cone of depression for several decades, the lateral movement of saline groundwater from the fringes of the area (particularly the northern area) toward the centre of the cone of depression has been relatively slow. This is clearly demonstrated on the northern boundary of the cone of depression. Here it exhibits a steeper gradient where it bounds the high salinity in the north.

The greatest impact on groundwater salinity has been point source pollution from leakage via defective wells. This has sometimes been misinterpreted as a total increase in groundwater salinity.

The results of a recent review of salinity information from approximately 199 wells sampled over the last 10–12 years are summarised in Table 2.

Table 2 Summary on the status of the 199 wells (Schuster and Gerges, 1999)

Wells	**T1**	**T2**
Wells backfilled before 1999	2	6
Wells that have had a permit issued to backfill in January 1999	–	1
Wells with abnormally high salinity	9	37
Wells with salinity below or equal to their natural salinity range	19	83
Wells requiring more annual salinity data for accurate analysis	6	21
Wells that could not be sampled or re-sampled	1	9
Wells still requiring identification/location confirmation	–	4
Well suspected of connecting two aquifers	–	1
Total	**37**	**162**

Other reasons for salinity increases include:

- Thin or non-existent confining beds separating the Tertiary aquifers from the Quaternary aquifers (namely, the Waterloo Corner – St Kilda area).
- Leakage via wells that have been completed across two or more aquifer systems.

Although salinity increases have been highlighted as a major threat to the basin, a large number of wells still pump groundwater that approximates the original background salinity across the region.

11.0 MAJOR ISSUES IN THE NAP AREA

1) The major threat to the T1 aquifer groundwater in the Waterloo Corner area is rising salinity. Groundwater salinity levels in this aquifer are highly sensitive to pumping, and intensive pumping will accelerate downward leakage of saline water from overlying Quaternary aquifers.

Continued urbanisation of the Little Para River will cause a considerable shift of groundwater license allocation. If the transfers continue to be concentrated in the Waterloo Corner area, further stress on this fragile aquifer will cause lowering of water levels accompanied by a leakage of more saline water into the T1 aquifer — to the detriment of present day growers.

2) In the T2 aquifer, leakage via corroded casing (point source) is the major cause of salinity increases. Recently, leaky wells have been identified; while some have been backfilled, others have been recommended for remediation. However, rehabilitation is costly. In some cases prolonged, steady and continuous pumping to waste from a rehabilitated leaky well, proves useful in restoring natural groundwater.

3) Decline in water levels is a major issue in the area, since water levels in the centre of the T1 aquifer have fallen by 25–30 m and in the centre of the T2 aquifer by 60–70 m. The decline is in response to intensive pumping, a high concentration of pumping wells in a small area and pumping during winter.

At present, during summer in the Virginia area, the cone of depression reaches the top of the aquifer which becomes locally unconfined. It is expected that a minor decline of water levels will occur in the centre of the area and the major decline may continue outside the centre of the cone. As the cone progressively expands, the unconfined situation may spread laterally covering a larger portion of the irrigation area.

12.0 RECOMMENDATIONS AND MANAGEMENT ISSUES

The hydrogeology of the NAP area is complex with recharge of the deep aquifers mostly via lateral through-flow from the basin's eastern margins. Vertical recharge from rainfall and surface water is of relatively minor significance.

The main threats to the NAP region groundwater are seen as:

- over use leading to depressed groundwater levels and well interference
- salinisation of groundwater in the principal aquifers T1 and T2 due primarily to leakage through corroded casing or wells that have not been pressure cemented.

The future potential uses for groundwater will increase from the T1 aquifer in the southern area, as the cost of mains water increases. The greatest increase in groundwater demand will come from large industrial users of water.

A future potential reduction in groundwater extraction from the T2 aquifer in the northern portion of the area is anticipated as a result of the introduction of Bolivar-treated effluent.

While this report provides the current best estimates of extractions and demonstrates the continuing decline in water levels in areas of heavy extraction, continual upgrading and monitoring of observation wells, particularly in areas under heavy and continuous stress, will be required to confirm the long-term trend. It will also be necessary to monitor the monthly–bimonthly extraction rates (particularly during the winter months) from the T1 and T2 aquifers to assess accurately winter extraction.

A review of the condition of water wells to assess leakage between aquifers is also important, particularly where the higher quality aquifers are under threat from aquifers of higher salinity.

ASR provides an opportunity for the conjunctive use of stormwater and treated effluent, for relatively safe storage in the local aquifers ready for demand. ASR can be used to enhance degraded groundwater salinity and water levels

Comprehensive water and salt balance studies are essential for sound future management of the area and a fully integrated numerical model is being developed to assist in future predictions.

The concept of sustainable yield still receives much debate, but it is currently defined in the State Water Plan 2000 as; *'the groundwater extraction regime, measured over a specified planning timeframe, that allows acceptable levels of stress and protects the higher value uses that have a dependency on the water'*.

In the NAP region, natural aquifer replenishment by low salinity recharge on the eastern margin is small in relation to current extractions (e.g. example it is estimated at 2930 ML/yr for the T2 aquifer). If extraction from the T2 aquifer (currently estimated at 13 500 ML/yr) is reduced to this level then a complete recovery of the potentiometric level would be observed. However, if extractions were reduced to equal the natural rate of aquifer replenishment the existing horticultural industry would be severely impacted.

Alternatively, if extraction from the T2 aquifer were decreased such that the cone of drawdown was reduced both in areal extent and to a maximum depth of about 50% of the present day cone (levels similar to those of the 1960s (Fig. 33)) the issues of well interference would largely be eliminated. Reduction in total extraction together with a concerted effort to rehabilitate or abandon leaky wells in accordance with the appropriate specifications would provide a long-term sustainable solution for the groundwater systems in the area.

The completion and appropriate documentation of the hydrogeological modelling of the system will provide a range of options for consideration by stakeholders in the area. On this basis, through consultation and negotiation with stakeholders an acceptable level of extraction can be arrived at which should maintain the viability of the horticultural industry and ensure the sustainability of the aquifer system for many decades.

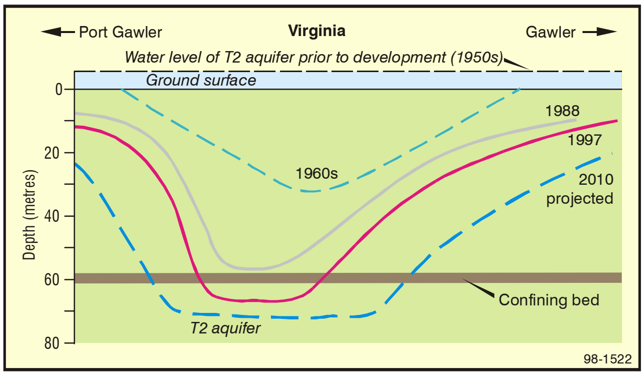

Figure 33 Diagrammatic cross-section of a cone of depression developed in the T2 aquifer since the 1950s

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