

Assessment of the groundwater resources in the non-prescribed areas of the South Australian Murray-Darling Basin

DEWNR Technical report 2015/09



Government of South Australia
Department of Environment,
Water and Natural Resources

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Steve Barnett

Department of Environment, Water and Natural Resources

July, 2015

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Department of Environment, Water and Natural Resources

GPO Box 1047, Adelaide SA 5001

Telephone National (08) 8463 6946
 International +61 8 8463 6946

Fax National (08) 8463 6999
 International +61 8 8463 6999

Website www.environment.sa.gov.au

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ISBN 978-1-922255-47-1

Preferred way to cite this publication

Barnett, S, 2015, *Assessment of the groundwater resources in the non-prescribed areas of the South Australian Murray-Darling Basin*, DEWNR Technical report 2015/09, Government of South Australia, Department of Environment, Water and Natural Resources, Adelaide

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1 Summary

The Non-Prescribed Regional Groundwater Assessments project aims to improve the understanding of the State's groundwater resources in SA. Over the years, extensive investigations into the hydrogeology of the Murray Basin have greatly increased the knowledge of the three main aquifer systems - the Renmark Group confined aquifer of Eocene age, the Oligo-Miocene Murray Group Limestone aquifer and the Pliocene Sands unconfined aquifer. These aquifers are mainly recharged in the high rainfall areas toward the basin margins with groundwater flowing under low hydraulic gradients along extended flowpaths before discharging to the River Murray, either by upward leakage from confined aquifers or direct hydraulic connection from the watertable aquifers. Groundwater salinities generally increase downgradient from the recharge areas where they are below 1 000 mg/L. Where groundwater discharges to the river, salinities are often over 20 000 mg/L which can add significant salt loads to the river, especially where the discharge is enhanced by upward leakage from a confined aquifer or by return flows from watertable mounds beneath irrigation areas. High groundwater salinities are also associated with areas of low topography where evaporative concentration occurred when watertables were higher during the very wet periods of the Pleistocene.

Basement structure, which is reflected in the modern surface topography by resurgent tectonics, can exert a strong influence on groundwater flow patterns and discharge mechanisms. In low-lying areas which overlie the deepest part of the Murray Basin near Loxton, the watertable is only a metre or so below ground level and consequently, these areas are the sites for evaporative discharge from the aquifer. Basement faulting can cause thinning of confined aquifers which promotes discharge by upward leakage and can also act as a barrier to groundwater flow in watertable aquifers.

Detailed investigations in the alluvium of the River Murray valley revealed that the floodplain is a zone of discharge for the regional aquifer systems by the process of evapotranspiration. This has led to concentration of groundwater salinities to greater than 35 000 mg/L with the subsequent storage of large quantities of salt in the floodplain. Salinization of low-lying areas on the floodplain has also occurred. These large quantities of salt may be mobilised to enter the river during or immediately after a flood event.

Under the Murray-Darling Basin Plan, South Australia has a requirement to develop Water Resource Plans (WRP) while having regard to the risks to the condition and availability of water resources, and to the strategies that manage or address those risks.

This hydrogeological assessment provides assistance for the development of the SA Murray Region WRP by informing a risk assessment of the capacity of the groundwater resource to meet environmental watering requirements, maintain the productive base of groundwater and connections to surface water where appropriate. Assessment of salinity impacts and prevention of water quality degradation is also required by a WRP.

The whole EMLR WRP region is covered by two Water Allocation Plans (WAPs) Policies in the WAPs aimed at maintaining baseflow and protecting ecosystems through buffer zones around assets for new drillholes, and the volumetric reduction of baseflow from the estimated recharge to establish extraction limits, should meet Basin Plan requirements.

All areas of low salinity groundwater where significant extractions are occurring are covered by the Mallee and Peake-Roby-Sherlock Water Allocation Plans (WAPs) which have similar requirements to the Water Resource Plan, namely assessing the needs of water dependent ecosystems and the impacts on connected water resources. Investigations for the Mallee WAP found no stygofauna or aquifer dependent ecosystems, mainly due to the large depth to the watertable. The Peake-Roby-Sherlock WAP describes only saline wetlands on the low-lying Coastal Plain that are connected to the shallow saline Quaternary Limestone aquifer (which is not currently used for extraction). Groundwater flow modelling has shown a low risk of adverse salinity impacts on the Murray Group Limestone and Renmark Group aquifers as a result of extraction.

Monitoring of groundwater levels and salinity are adequate to assess the condition of the resource and the effectiveness of the management policies in the WAPs.

2 Introduction

The Water for Good plan (Government of South Australia, 2009) states that resource assessment, monitoring and management of non-prescribed groundwater resources are crucial and necessary elements which will assist in achieving sustainable use of the resource. The Department of Environment, Water and Natural Resources (DEWNR) has lead agency responsibility for ensuring the sustainable management of groundwater resources of South Australia and has developed the Groundwater Program to fulfil responsibilities under the Natural Resources Management Act 2004 and to address water security issues facing the State.

There is only limited understanding of groundwater resources in most non-prescribed regions across the State. Current knowledge gaps regarding the quantity and quality of groundwater resources present significant barriers to the management and future development of many groundwater systems. Addressing these gaps is especially important due to anticipated increases in demand for water, changes in land use and potential impacts associated with a changing climate.

Another driver for this assessment is that under the Murray-Darling Basin Plan, South Australia has a requirement to develop a Water Resource Plan (WRP) while having regard to the risks to the condition and availability of water resources, and to the strategies that manage or address those risks.

2.1 Objectives

The objective of this project is to improve the understanding of non-prescribed groundwater resources in the South Australian Murray-Darling Basin Natural Resources Management (SAMDBNRM) Region by integrating and describing the existing data and knowledge about the non-prescribed groundwater resources. This assessment aims to compile geological and hydrogeological data giving particular attention to the identification of major hydrogeological units and related groundwater information. Based on the available information, discussions on groundwater salinity, level and yield are supported by a selection of map products. The lower salinity groundwater within the NRM region is prescribed within three Prescribed Wells Areas.

This report will also assist in the development of the SA Murray Region WRP by informing a risk assessment of the capacity of the groundwater resource to meet the requirements outlined in the Basin Plan. Figure 1 presents the location of the SA MDB NRM Region, SA Murray Region WRP area and the three Prescribed Wells Areas.

2.2 Previous work

The first observations on the geology of South Australian portion of the Murray Basin were made by Captain Charles Sturt (1833) during his history-making journey down the River Murray, where the flat-lying Tertiary limestones of the Murray Group are exposed in the gorge tract downstream from Overland Corner. Tate (1885) followed with notes on the stratigraphy of his "Murravian" Series at several locations along the course of the Murray. The first of several major regional investigations was carried out by Barnes in the central part of the Murray Basin in 1946 to "critically examine the underground waters in counties Albert and Alfred, and to determine whether these waters could be utilised to greater advantage" (Barnes, 1951).

During the post-war years, as agriculture expanded, so too did drilling activity throughout the Murray Basin. A request from the Department of Lands to determine the availability of groundwater in the Ninety Mile Desert to the west of Tintinara, led to the drilling of a total of 125 investigation wells (O'Driscoll and Shepherd, 1960).

O'Driscoll commenced examination of some 10 500 well records from the Murray and Otway Basins and arranged the systematic collection of drilling samples for geological logging and palaeontological examination. This enabled the establishment of a stratigraphic framework (Ludbrook, 1960) which greatly clarified the hydrogeological appreciation of the basin which was previously based on inadequate data. Numerous geological cross-sections were prepared and the detailed hydrogeology of each county was presented (O'Driscoll, 1960).

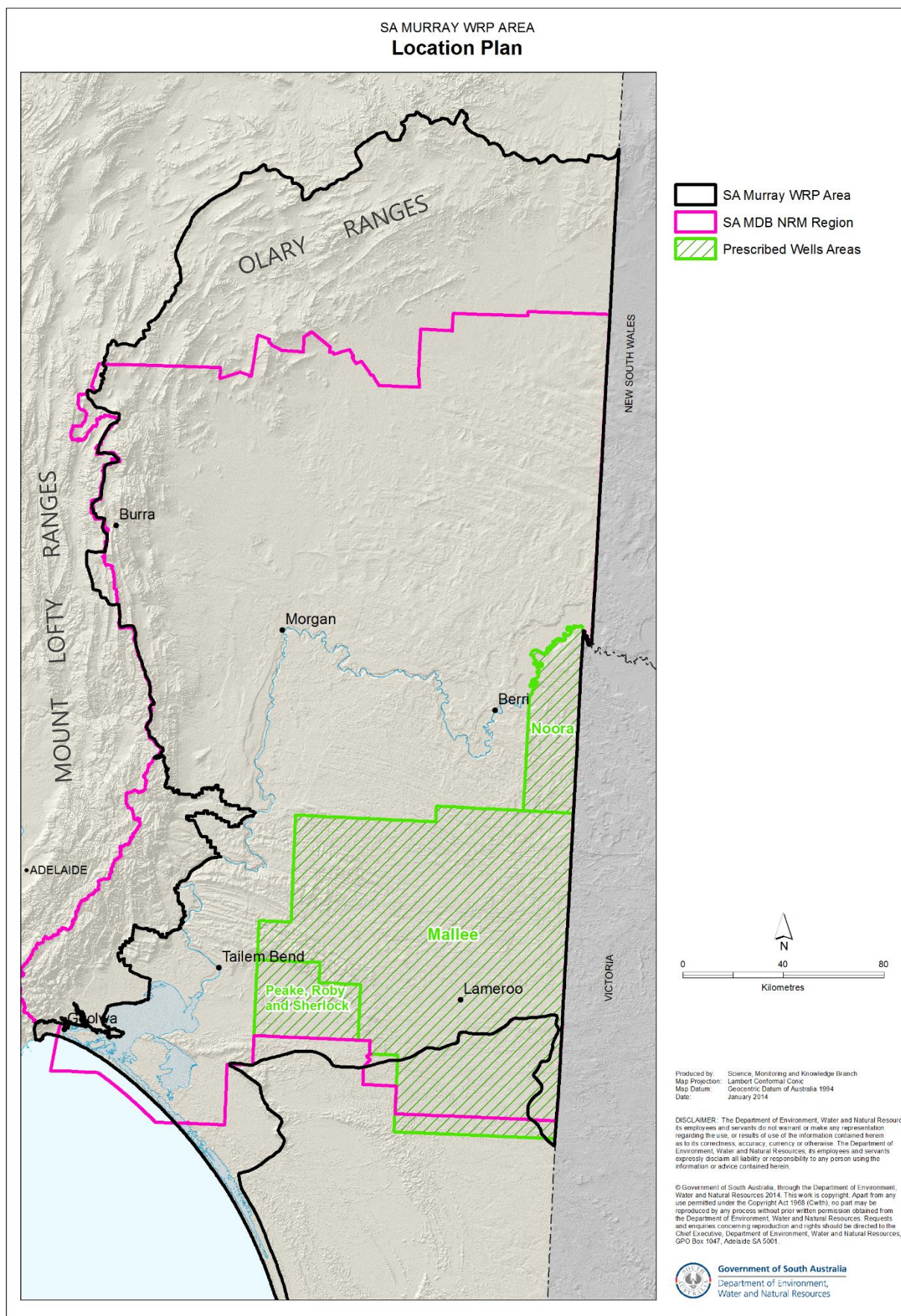


Figure 1. Location plan

The 1967/68 drought and its disturbing effect of increasing River Murray salinity, focused the attention of hydrogeological investigations on localised salinity-based projects for the next ten years. Impetus for this trend began in 1967 when the River Murray Commission appointed consultants to investigate the causes, occurrence and effects of salinity on the River Murray and its users. Intensive studies by the consultants and various Government Departments were carried out with the hydrogeological emphasis aimed at the relationship between groundwater and the river. In fact in 1967, it was not known definitely whether or not groundwater discharged to the river.

In the latter half of 1978, the Bureau of Mineral Resources sought the co-operation of State geological surveys and water authorities in carrying out a joint long-term study to improve the understanding of the groundwater systems of the Murray Basin as a single entity, unencumbered by arbitrary State boundaries. The following year, 1979, it became accepted in South Australia that a proper understanding of the regional hydrogeology was essential in the understanding and treatment of localised groundwater problems and a regional investigation program was commenced.

The initial phase of the investigation involved a comprehensive review of all available existing hydrogeological data for the three main aquifer systems (Renmark Group, Murray Group and Pliocene Sands) for the whole of the Murray Basin in South Australia. This considerable task entailed the extraction of useful hydrogeological and stratigraphic data from a variety of sources. Some 7000 individual water well records were examined, together with published and unpublished Departmental reports and results from mineral exploration drilling by private companies.

The compilation of these data assessment reports identified areas where hydrogeological information was lacking. Where possible, existing wells were surveyed and some were geophysically logged to provide potentiometric surface elevations and stratigraphic information. The remaining gaps in the data network were filled by a comprehensive drilling programme. Over a period of 10 years, over 170 investigation wells were drilled throughout the Murray Basin in South Australia. These were drilled by departmental rotary rigs and completed as observation wells to monitor groundwater salinities and potentiometric heads in each of the three aquifer systems. Every hole was geophysically logged with composite logs and drilling results being presented in a series of progress reports (Edwards 1979, 1981a & b, 1982a & b, 1983; Barnett 1988a & b, 1989a and 1992a).

The information obtained from these investigations was far more widespread and more detailed than that obtained before, and resulted in a much greater understanding of the groundwater systems in the Murray Basin. This enabled the production of hydrogeological maps at a scale of 1:250 000 in conjunction with Australian Geological Survey Organisation and the water authorities of NSW and Victoria. Information on groundwater salinity and flow directions for all the major aquifers, hydrographs and subsurface geology was published for use by natural resource managers, groundwater consultants, engineers, farmers and well drillers (Barnett 1992b, 1993, 1994a & b; Cobb and Barnett, 1994).

3 SA MDB NRM Region

The SA MDB NRM region is one of eight natural resources regions in South Australia and is located in the south-western portion of the Murray-Darling catchment. It covers about 56 000 km² and extends from the Victorian and New South Wales borders to the catchment boundary along the Mount Lofty Ranges, from the Rangelands in the north to the Murray Mallee and Murray Mouth in the south (Fig. 1.). With the exception of the Olary Ranges to the north, it encompasses all of the SA Murray WRP area. The region supports a population of approximately 125,000 people and is one of South Australia's most ecologically diverse and agriculturally productive regions (SA MDB NRM Board, 2013). The River Murray, South Australia's most substantial and important surface water resource, flows through the region.

3.1 Climate

The SA MDB Region experiences a temperate Mediterranean climate with hot, dry summers and cool, wet winters. Most of the region could be classes as semi-arid. Table 1 lists the climatic averages for several towns distributed widely across the region. Most rain falls in winter when cold fronts and low pressure systems travel across the basin from the west. There is consequently a strong rain shadow effect caused by the Mount Lofty Ranges resulting in a sharp decrease in rainfall from the ranges to the plains in the east (compare Mt Barker and Lamerook rainfall). Rainfall is greatest along the south-west coast and decreases steadily in quantity and frequency with increasing distance from the coast to the north (compare Meningie and Yunta rainfall). The coastal areas experience a milder and wetter climate, while inland conditions are hot, dry and cold in winter (compare Meningie and Yunta temperatures). Mean annual rainfall (Fig. 2) varies from less than 250 mm/y in the north to around 500 mm/y in the south. Mean annual Class A evaporation rates ranges between 1600 mm/y in the south to about 2600 mm/y in the north of the region.

Table 1. Climatic averages for a selection of SA MDB localities (Bureau of Meteorology, 2010)

Locality	Summer Max Temp. °C	Winter Min Temp. °C	Annual Rainfall (mm)	Evaporation (mm)
Meningie	25.6	7.0	470	1640
Lamerook	30.1	4.8	383	1960
Mt Barker	26.4	4.9	764	1900
Yunta	31.9	3.5	236	2530
Renmark	31.6	5.7	260	2270

3.2 Topography

The topography of the non-prescribed area is dominated by the Mount Lofty and Olary Ranges which form highlands around the northwestern margin of the sedimentary plains of the Murray Basin. In the southwest, a low-lying coastal plain up to 30 m above sea level was formed by a Pleistocene marine transgression. Further to the north, an extensive flat to gently undulating sand plain rises to about 150 m elevation at its northernmost extent at the foothills of the Olary Ranges (Rogers, 1980). There are numerous northwest trending strand-line features and smaller aeolian dunes. The River Murray has incised a valley up to nine kilometres wide and up to 45 m deep.

3.3 Land use

In 2008, the major land uses in the region were grazing of modified pastures (25%) and cropping (19%). Grazing of natural vegetation (21%) and nature conservation (20%) are also major land uses. Irrigated production comprises 2% of the region and mainly occurs adjacent the Murray River and Angas Bremer catchments (mainly using surface water resources), and in the Mallee PWA using groundwater resources (SA MDB NRM Board, 2013).

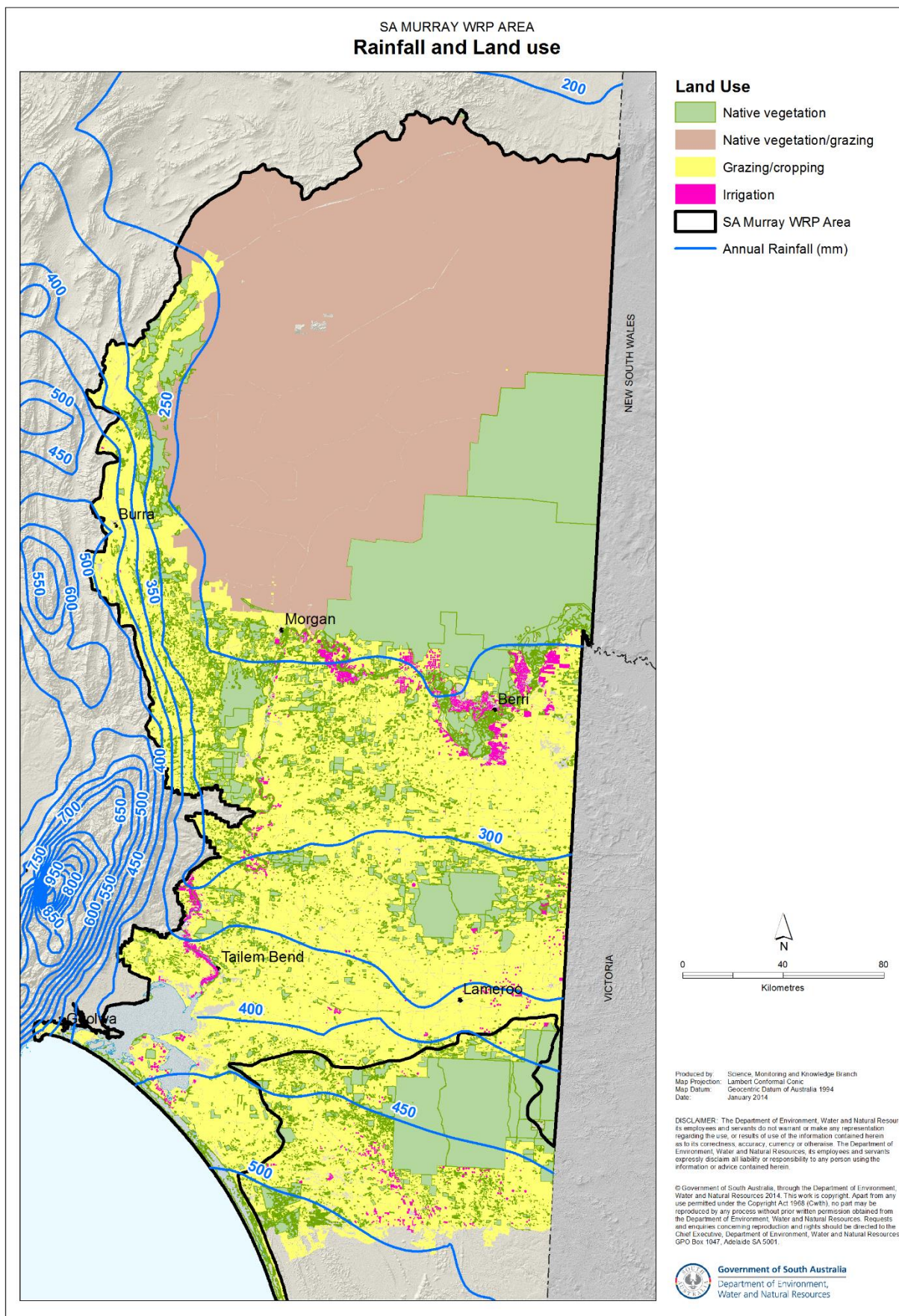


Figure 2. SA MDB NRM region - rainfall and land use

Between 2003 and 2008, large areas of grazed natural vegetation north of the River Murray were converted to nature conservation, largely due to the inclusion of Gluepot Reserve, Calperum Station and Taylorville Station as protected areas under the Commonwealth Environment Protection and Biodiversity Conservation Act 1999. Another major change was the significant reduction in land area used for grazing modified pastures across the SA MDB NRM region and significant increase in the land area used for cropping. It is noted, however, that both of these land use classes may include land in a rotation system (SA MDB NRM Board, 2013).

3.4 Water Resources

Because of the semi-arid climate and generally sandy soils, there are few surface water resources available apart from the River Murray and the associated reticulated water supply systems. Ephemeral creeks flow out of the highlands usually only in very wet years and discharge onto the plains for short distances before dissipating by evaporation or infiltration into permeable sediments if they exist. Only the largest actually reach the River Murray (e.g. Burra Creek) and even then only in exceptionally wet years if at all. No streams reach the river between Morgan and the Marne River because uplift along the Morgan Fault has created a barrier to eastward flow, with the resultant formation of infrequently filled lakes and claypans (eg Lake Short and Craigie Plains). This low uplifted block is 30 m high and several kilometres wide (Fig. A2).

Because of the scarcity of surface water resources, there is consequently a heavy reliance on groundwater for stock and domestic supplies where the salinity is suitable.

4 Geology

The Murray Basin is a relatively low-lying, saucer-shaped intra-cratonic basin containing Cainozoic sediments deposited in shallow-marine, fluvio-lacustrine and aeolian environments. These sediments attain a maximum thickness of 600 m over the Renmark Trough although individual units are generally thin, continuous, and flat lying. The Cainozoic sequence is mostly underlain by the Cambrian Kanmantoo Group which form poorly defined infrabasins preserved in graben-like troughs and depressions (Brown & Stephenson, 1991) which contain sedimentary rocks ranging in age from Silurian to Cretaceous. Framework tectonics provided the primary control on development of the basin, however at least three major depositional sequences display an apparently close correlation with global eustatic rises and falls in sea level (Brown, 1985). The western and northern basin margins in South Australia are formed by Precambrian and Cambrian rocks of the Mount Lofty-Olary Ranges. To the south, the basin is partly separated from the thicker Otway Basin sequence by the Padthaway Ridge (Fig. A1).

The Cainozoic sediments form an extensive blanket over the whole of the Murray Basin. Three major depositional sequences have been identified within the Tertiary succession as shown in Figure 3, each containing genetically related formations, separated by disconformities (Ludbrook 1961; Brown and Stephenson, 1991):-

1. Palaeocene - Eocene to Lower Oligocene,
2. Oligocene to Middle Miocene, and
3. Late Miocene to Pliocene.

Each sequence forms a thin but continuous veneer which has been deposited on a topographically flat, low-lying platform. Brown and Stephenson (1991) contend that the sediments form "a thin platform cover succession rather than a true basinal sequence". Quaternary sediments were deposited over a number of different environments, ranging from marine through lacustrine to colluvial.

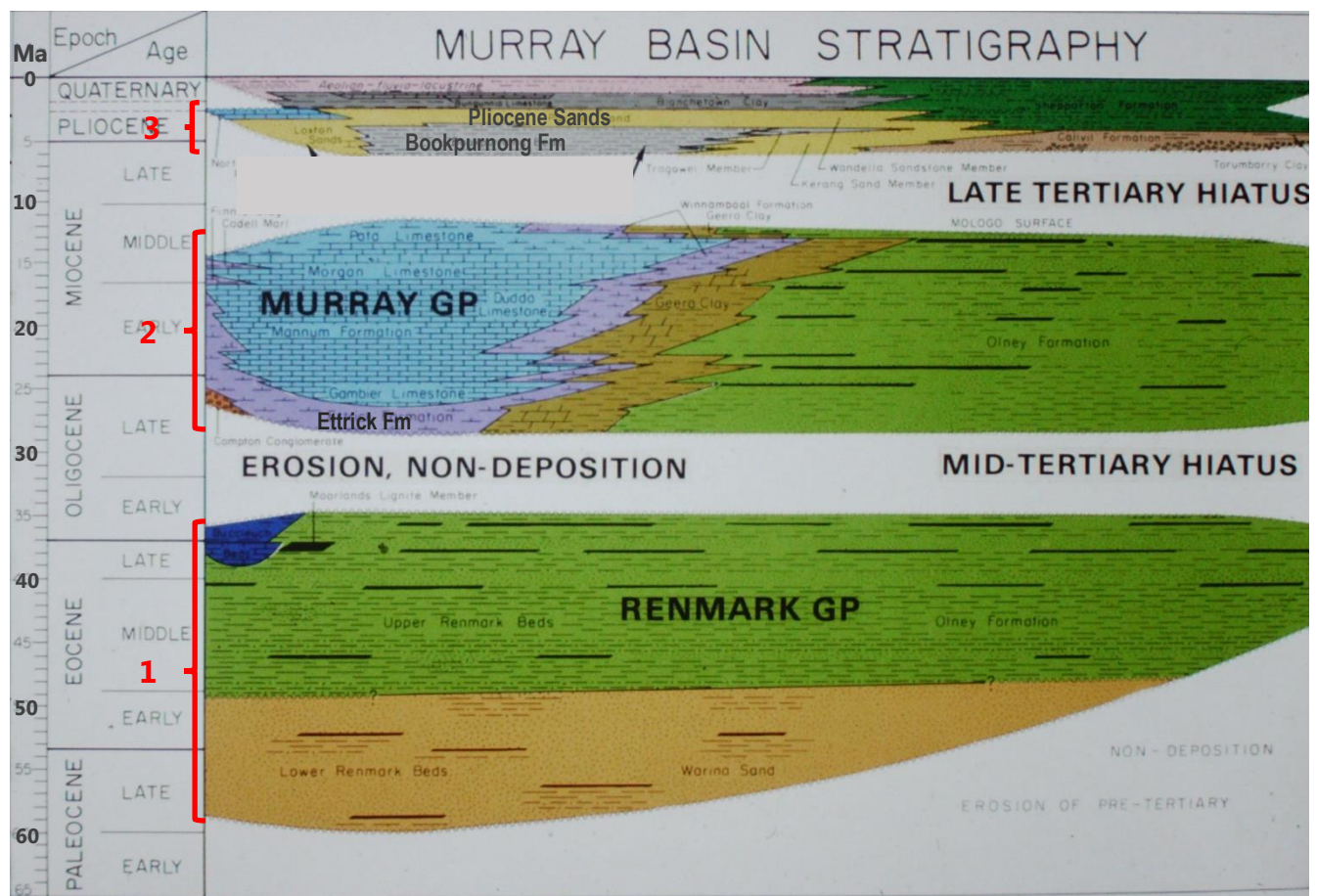


Figure 3. Murray Basin depositional sequences

Figure 4 displays geological cross sections through the Murray Basin. The north-south section is located close to the SA border with NSW and Victoria and shows how the various units thicken and deepen toward the deepest part of the basin, namely the Renmark Trough. The east-west section runs from near Eudunda in the ranges to Renmark through Waikerie and depicts the block faulting on the western margin of the basin and thin sedimentary sequences.

The transmission of basement structures to the overlying, essentially undeformed Cainozoic sediments by resurgent tectonics has occurred throughout the basin with pronounced results. The course of the River Murray has been profoundly affected by jointing within the Murray Group limestone (O'Driscoll, 1960) as well as the gentle warping of the Tertiary sediments overlying basement structures such as the Morgan Fault, the Hamley Fault, and the Murrayville Monocline (Twidale, Lindsay and Bourne, 1978).

In fact, the topography of the present land surface also reflects that of the pre-Tertiary basement (Fig. A1) as a result of this process, together with compaction of the finer grained sediments in the deeper parts of the basin. A good example is the saline playa area at Noora, 25 km east of Loxton. This is one of the lowest points in the Murray Basin as a whole (outside the river floodplain) at about 18 m AHD, and is situated over the Renmark Trough which is the deepest part of the basin where the Tertiary sediments are thickest. Similarly, the low-lying area inundated by Lake Alexandrina overlies up to 500 m of unconsolidated Permian sediments.

More detailed descriptions of the geology of the various units is presented in Appendix A.

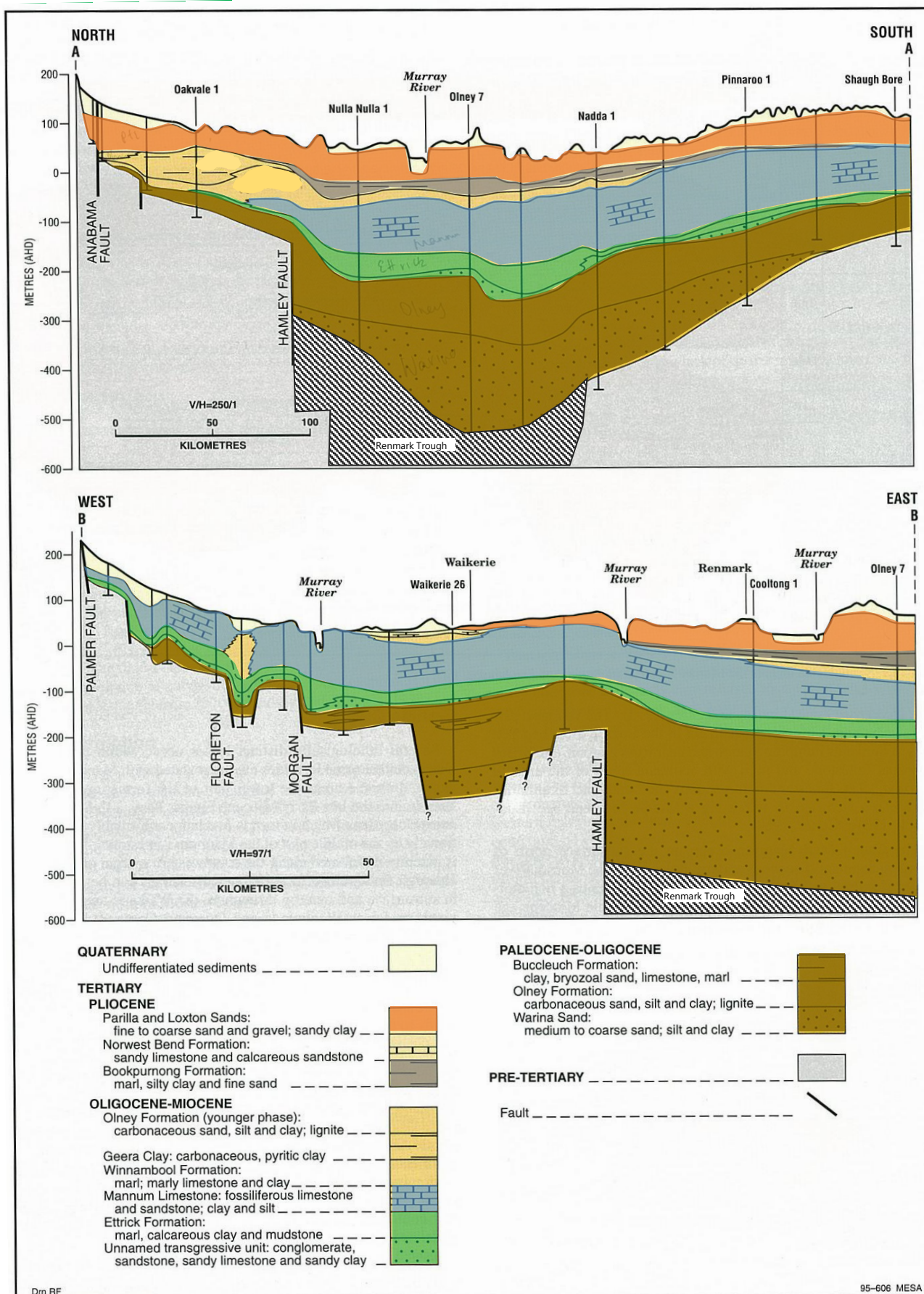


Figure 4. Murray Basin geological cross sections (after Barnett, 1989)

5 Regional hydrogeology

The SA MDB catchment contains the highland surface water catchments of the northern Mount Lofty and Olary Ranges which comprise fractured rock aquifers of various lithologies, and sediments within the Murray Basin.

The Murray Basin contains a multi-layered regional groundwater system through which groundwater flows under low hydraulic gradients from the basin margins toward the River Murray which acts as a drain, and is consequently the focus for groundwater discharge. Normally these discharge rates are low because of the low hydraulic gradients from the distant recharge areas. There are four main regional aquifers separated by two confining layers. Figure 5 shows the regional hydrogeology along an east-west section through the basin. The main hydrostratigraphic units are briefly described below in order of increasing age which also corresponds to increasing depth below the ground surface.

Quaternary Limestone aquifer:- this unconfined aquifer was deposited on the low-lying Coastal Plain in the southwest margin of the basin. It is hydraulically connected with the underlying Murray Group Limestone and contains groundwater of varying quality with flow toward the Coorong and Lower Lakes under low gradients.

Pliocene Sands aquifer:- an unconfined aquifer which is saturated only in the northeast of the SA portion of the Basin. The unit comprises unconsolidated to weakly cemented fine to coarse sand. The groundwater flow is generally towards the River Murray under low gradients, except where watertable mounds exist beneath irrigation areas adjacent to the river. The salinity in the aquifer is generally over 20 000 mg/L.

Bookpurnong Formation (confining layer):- this unit occurs only to the northeast where it dips down gradually to the east and increases in thickness. It consists of plastic silts and shelly clays that confine the underlying limestone aquifer.

Murray Group Limestone aquifer:- this most widely studied aquifer comprises a consolidated, highly fossiliferous, fine to coarse limestone. It is mostly unconfined and has been developed for stock, domestic, irrigation and town water supplies because it contains low salinity groundwater over large areas. Recharge occurs from high rainfall areas around the basin margins such as the Mount Lofty Ranges to the west and in southwest Victoria to the southeast. Groundwater flows under low hydraulic gradients to the River Murray where it discharges and contributes to the increasing salinity of the river. Salinities increase downgradient, from below 1000 mg/L at the recharge areas to over 20 000 mg/L adjacent to the river;

Ettrick Formation (confining layer):- a low permeability layer between the Murray Group Limestone and the underlying confined aquifer, consisting of a glauconitic and fossiliferous marl;

Renmark Group aquifer:- a confined aquifer comprising unconsolidated carbonaceous sands, silt and clay. It has been developed for stock and domestic supplies only around the basin margins, where it is relatively shallow and contains groundwater that is usually of lower salinity than that within the overlying limestone aquifer which is sometimes saline. Groundwater flow is generally from the basin margins toward the river where discharge occurs to the overlying aquifer by upward leakage. Salinities are in the range of 10 000 - 20 000 mg/L.

Emphasis has been placed in this report on aquifer systems rather than detailed stratigraphy. Consequently, several geological units have been consolidated into a broad hydrostratigraphic units with a common lithology.

The water level elevation and salinity contours for each of the main three aquifers (Renmark Group, Murray Group Limestone and Pliocene Sands) are presented in Figures 6 – 8 respectively.

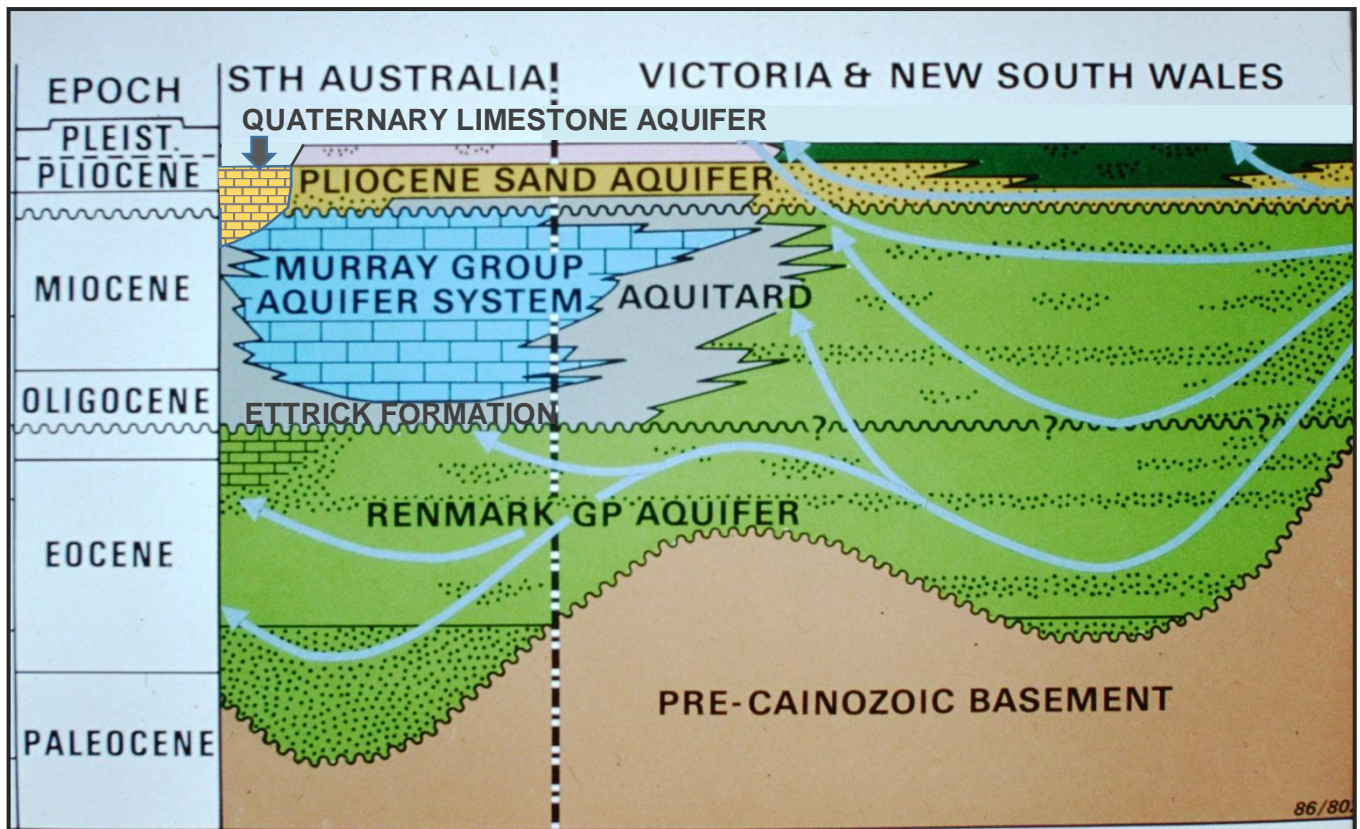


Figure 5. Murray Basin regional hydrogeology

The Murray Basin in South Australia can be divided into the following six reasonably distinct hydrogeological regions, each with its own unique characteristics (Fig. 9). The hydrogeological setting of each of these regions will be discussed in Sections 5 to 10 of this report.

- 1) Mallee Region - has the highest groundwater usage because of the large area of low salinity groundwater available. The geological sequence is fully developed and all three aquifer systems are present.
- 2) Coastal Plain Region - a low lying area on the southwest basin margin which has been subject to several marine transgressions. Groundwater salinities are highly variable and is at risk to extensive dryland salinisation after wet years.
- 3) Upper Murray Region - where most of the interaction between saline groundwater and the River Murray occurs, exacerbated by watertable mounds beneath irrigation areas. It overlies the deepest part of the Murray Basin.
- 4) Western Margin - has a condensed geological sequence with shallow basement. Consequently groundwater supplies and salinities are highly variable.
- 5) Northern Region - an area of high groundwater salinities and poor aquifers.
- 6) Highlands - the area of fractured rock aquifers bounding the sedimentary aquifers to the north and west.

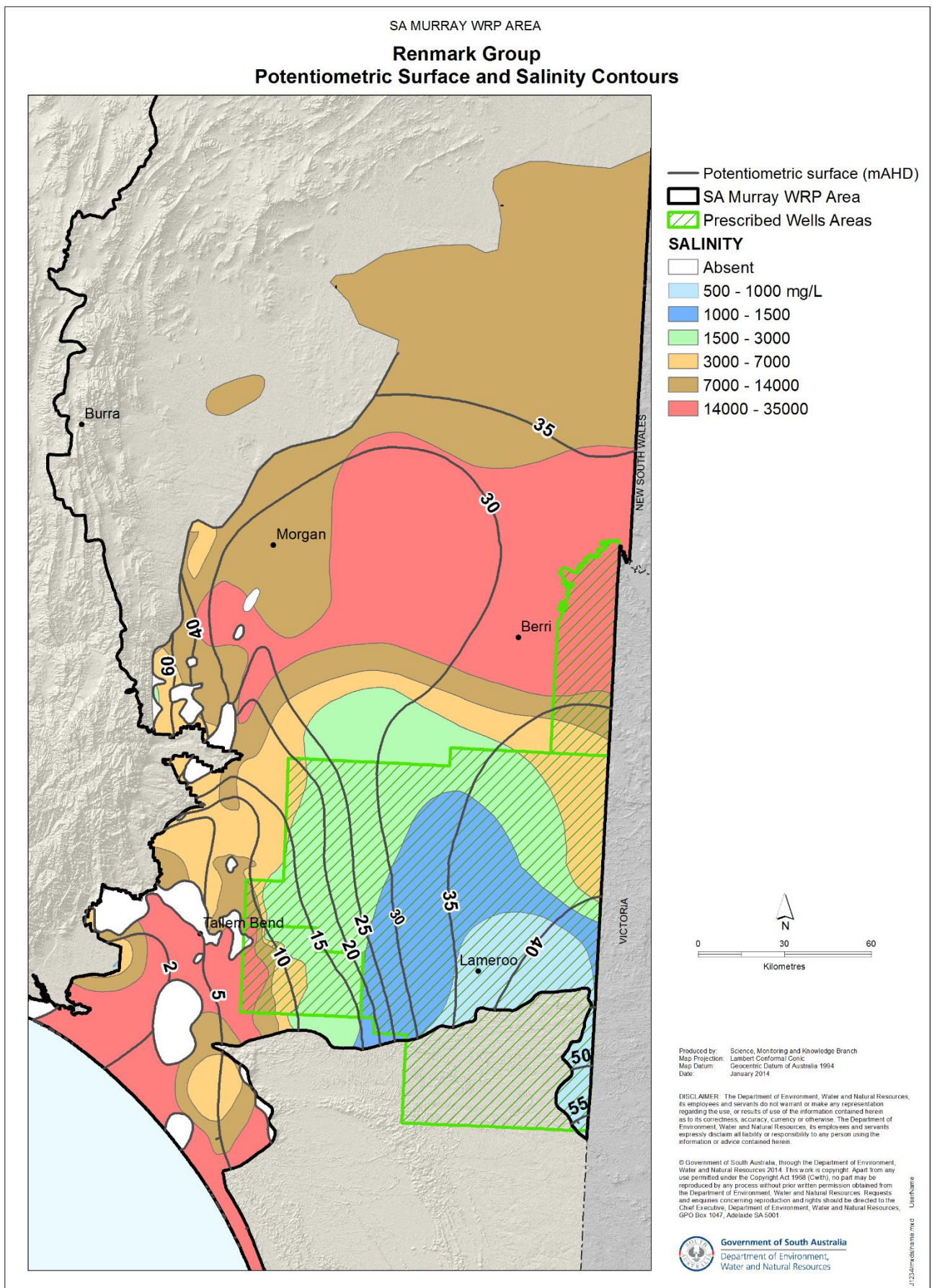
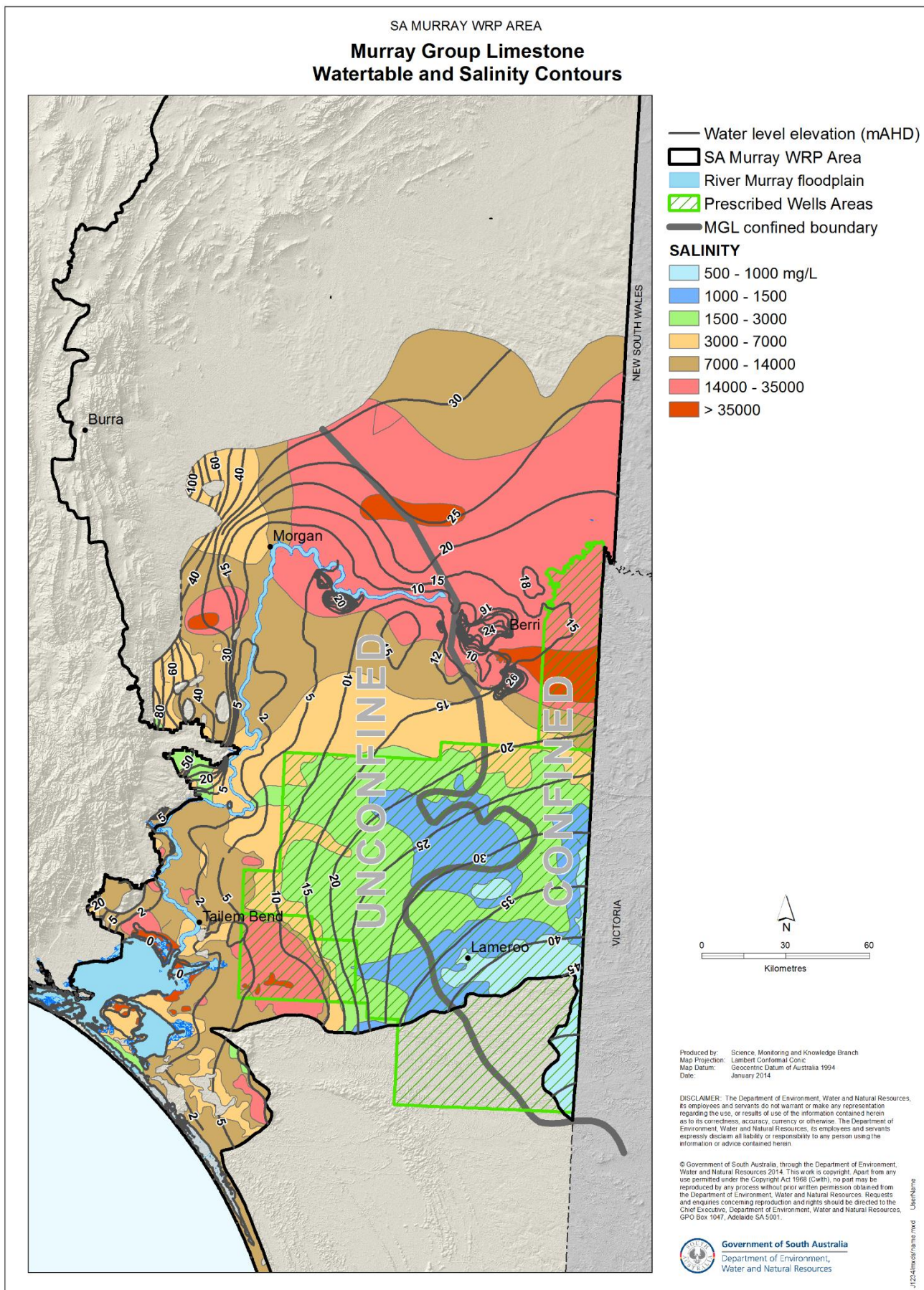


Figure 6. Renmark Group confined aquifer – potentiometric surface and salinity contours



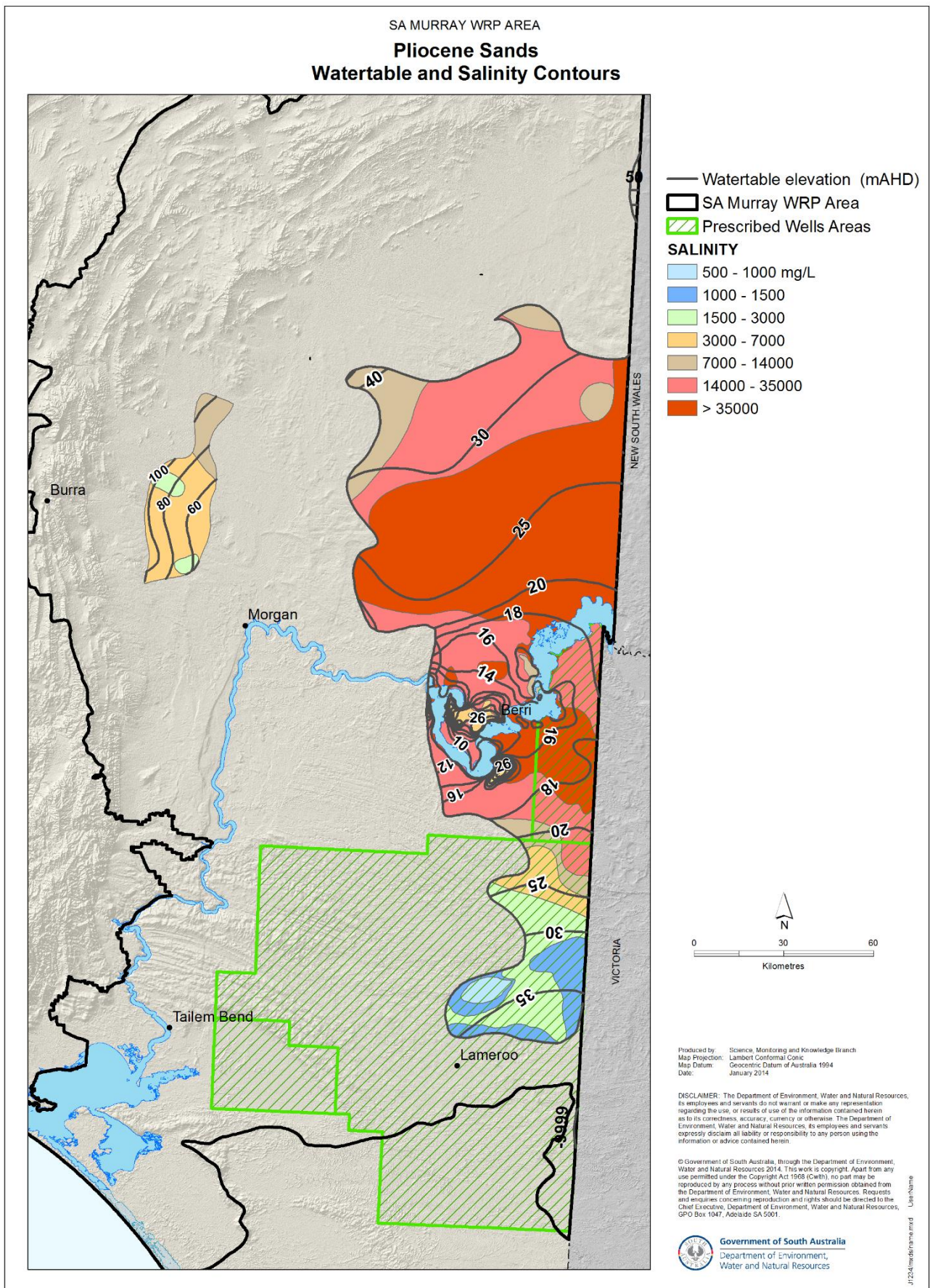


Figure 8. Pliocene Sands aquifer – watertable elevation and salinity contours

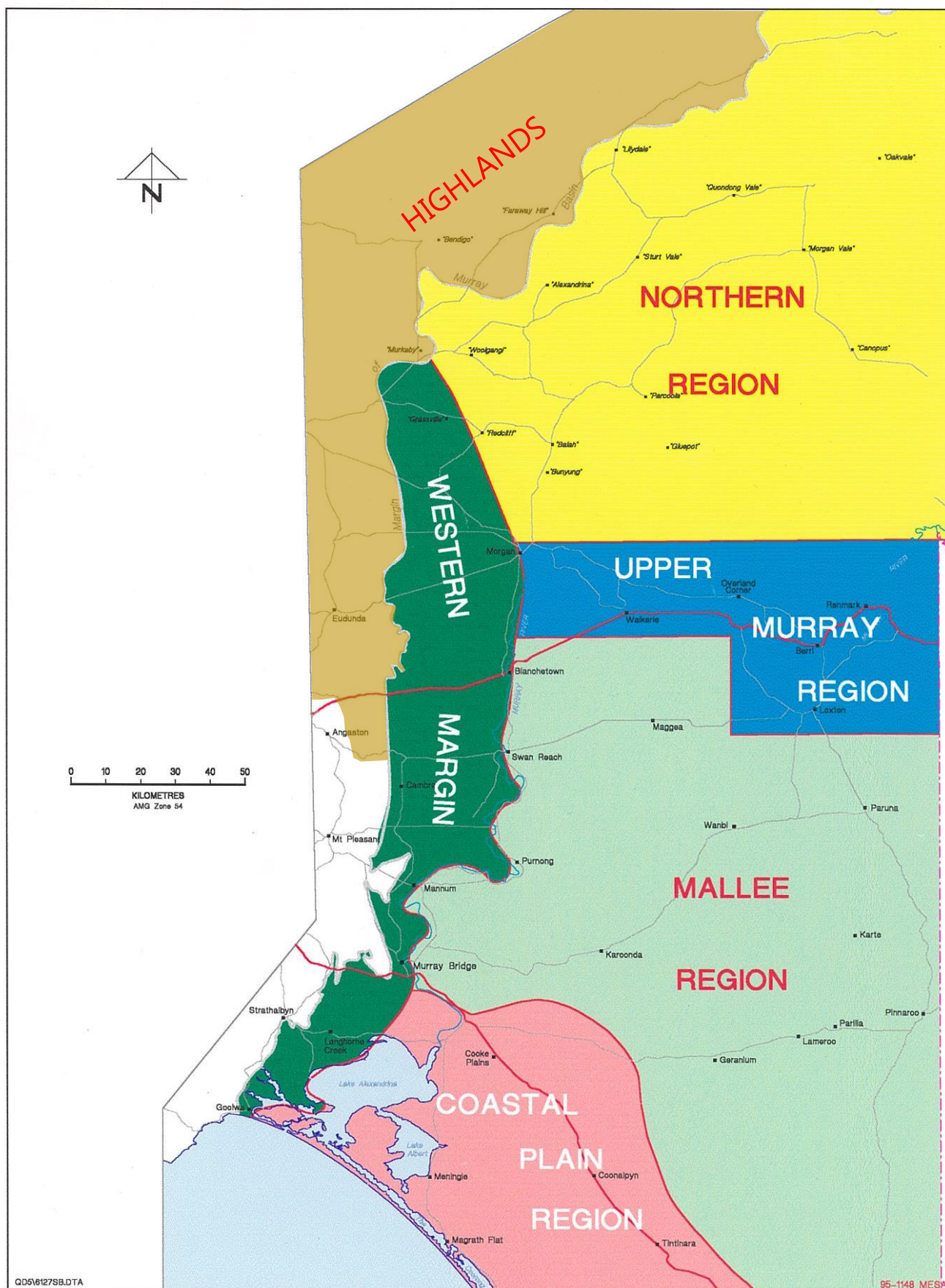


Figure 9. Murray Basin hydrogeological regions

6 Mallee Region

This region is the best understood of the Murray Basin regions because of the large areas of good quality groundwater which have been extensively utilized for stock, domestic, town water supply, irrigation and more recently, mining purposes. The area consists of a flat to gently undulating plain about 40 to 125 m above sea level with abundant east-west trending aeolian sand dunes and occasional northwest trending ridges representing Pliocene strand features.

Much of the original vegetation of mallee, broombush, heath and ti-tree has been cleared for cereal cropping and sheep grazing. Considerable areas of mallee scrub and small stands of native pine and sheoak remain in conservation parks in the eastern and western areas respectively (Fig. 2).

Rainfall decreases from about 450 mm per annum in the south, to about 250 mm in the north. There is negligible surface drainage because the relatively low rainfall is absorbed locally by the predominantly sandy soils, however small freshwater soaks occasionally occur at the base of sand dunes which are underlain by clay soils. These soaks were more than likely used by Aborigines in their travels across the otherwise arid Mallee landscape between South Australia and Victoria.

The Mallee Region encompasses some of the deepest parts of the Murray Basin. The basement, which comprises mainly Kanmantoo Group metamorphics and isolated granitic and ultrabasic intrusives, deepens from the Padthaway Ridge outcrop in the southwest, to below - 400 m AHD over the Renmark Trough to the northeast. The overlying Tertiary units also deepen and thicken in this direction, as seen in the structure contours of the various units presented in Appendix A. A representative log depicting the hydrostratigraphic units and their thicknesses is shown in Figure 10.

A drilling programme was carried out in 1983 to improve the understanding of the area with 11 holes being completed in the Renmark Group confined aquifer. Composite logs are presented in Barnett (1989a). A comprehensive observation network was also established throughout the Mallee to monitor the effects of irrigation.

The management of the good quality groundwater resources in the Mallee occurs at several levels. At the State level, the Border Groundwater Agreement Review Committee jointly manages the groundwater resources in SA and Victoria, 20km either side of the State border. Among other duties, this Committee establishes the Permissible Annual Volume (PAV) for the various management zones along the border, which is the upper limit for groundwater extractions. At a regional level in the Mallee Prescribed Wells Area, the methodology used in the Border Zones to determine PAVs has extrapolated to set extraction limits under the Water Allocation Plan (WAP). More recently, the Basin Plan which is required to establish sustainable diversion limits for all the groundwater resources within the Murray-Darling Basin, adopted the extraction limits established in the Mallee WAP.

Because of low recharge from rainfall, the management approach took advantage of the large volumes in storage by adopting a controlled depletion or mining policy of volumes equivalent to an unconfined drawdown averaged over the whole region of no more than 5 cm/yr. After taking into account the derived inflows, outflows and interaquifer leakage volumes from the numerical groundwater flow model, pumping the maximum PAV every year would lead to a depletion in storage of only 15% after 300 years.

6.1 Renmark Group Confined Aquifer

Very few private wells intersect the confined aquifer because of its depth and unreliable yield. There are no licensed extractions from this aquifer within the Mallee PWA. Most of the current understanding was obtained from the Departmental drilling program (Barnett, 1989a). The aquifer deepens and thickens toward the northeast (Figs. 4 and A4).

Groundwater movement is from the high rainfall recharge area of the Dundas Plateau in southwest Victoria, in a westerly to northwesterly direction toward the River Murray where it discharges by upward leakage into the unconfined limestone aquifer. The potentiometric contours (Fig. 6) indicate a very low gradient to the north which is a result of the large thickness (up to 250 m) and hence high transmissivity of the aquifer. However to the south, the westerly gradient is quite steep as the aquifer thins toward the Padthaway Ridge.

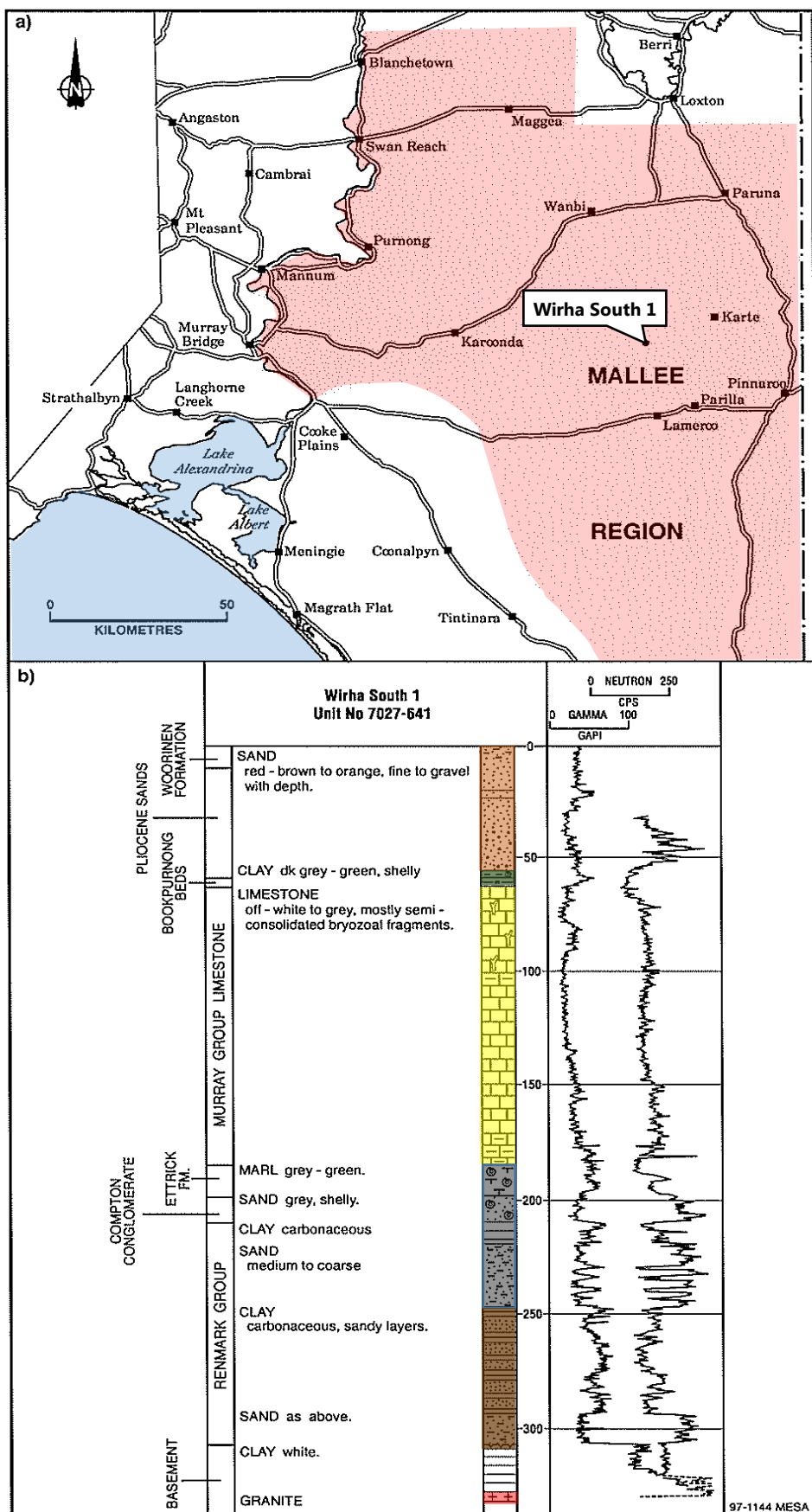


Figure 10. Mallee representative composite log – Wirha 1

The salinity contours (Fig. 6) show the existence of a large area of low salinity groundwater within the boundary of the Mallee PWA which becomes more saline downgradient towards the west and northwest. Where the aquifer wedges out against rising basement in the Padthaway and Taillem Bend areas, salinities increase rapidly to 10 000 -15 000 mg/L. O'Driscoll (1960) observed that the increase in salinity downgradient is accompanied by a change from a bicarbonate type groundwater to a dominantly chloride type and postulated freshening of the original connate waters by bicarbonate rich recharge waters. More recent information suggest that there has been sufficient time since deposition for the connate waters to have been flushed out of the aquifer. The increase in salinity reflects the trend in the overlying limestone aquifer and indicates mixing by downward leakage, especially when the watertable in the limestone aquifer would probably have been higher than the Renmark Group potentiometric head during the wetter periods of the Pleistocene.

No aquifer parameters are available for the Renmark Group confined aquifer in the Mallee region although modelling has suggested hydraulic conductivity values in the range of 0.5 to 5 m/day depending on the lithology (clayey sand to clean sands).

6.2 Ettrick Formation Confining Layer

This unit is continuous over the whole area and conforms to the general trend of deepening and thickening to the northeast. The glauconitic marls thicken from about 10 m in the south and southwest to 30 - 40 m to the northeast as depicted in the hydrogeological cross-sections (Fig. 4). The confining layer is occasionally absent, thins locally and sometimes contains sandy lenses which may allow better interconnection between the confined aquifer and the overlying watertable aquifer, depending on the thickness of the lignitic clay which is invariably found at the top of the Renmark Group.

6.3 Murray Group Limestone Aquifer

This widely developed aquifer is unconfined in the western half of the region but in the eastern half, it is confined by the thin clays of the Bookpurnong Formation confining layer (Fig. 7). In this area, the first water cut in the limestone aquifer rises up to 10 m inside well casings with no recorded water table in the overlying sediments. Most of the stock and domestic wells penetrate only the top few metres of the aquifer but town water supply wells and most irrigation wells are fully penetrating.

Similar to other units, the limestone deepens and thickens to the northeast (Figs. 4 and A6). Within the Mallee PWA, the limestone aquifer is up to 140 m thick. The potentiometric contours show groundwater movement radiating from the high recharge areas in the Dundas Plateau area of southwest Victoria (Fig. 7). Groundwater movement to the north and northwest occurs under fairly low gradients with discharge to the River Murray floodplain. To the west, gradients are steeper in response to decreasing hydraulic conductivity toward the Coastal Plain.

There has been ample time for any connate water to be flushed through the aquifer system since the last marine transgression which occurred about two million years ago during the Pliocene. It is assumed that watertable gradients have not been significantly lower than present ones for any great period of time. In fact, during the Ice Age when sea level was some 120 m lower than present, watertable gradients would have been steeper and hence groundwater flow rates would have been higher.

The trend of increasing salinity downgradient is quite apparent in Figure 7. Large areas to the southeast within the Mallee PWA are below 1000 mg/L with a gradual increase to the west and northwest to high values where the watertable discharges to the River Murray. These salinities range from 6000- 10 000 mg/L downstream of Morgan to 15 000- 20 000 mg/L between Morgan and Overland Corner. It has been postulated that this increase in salinity downgradient is caused by the gradual addition of meteoric salt from rainfall. Leaney and Allison (1986) found a log-normal distribution for chloride in some 130 wells in the Waikerie - Wanbi area which suggests the major source of chloride is from atmospheric accretion.

Yields from the limestone aquifer vary from windmill supplies to over 60 L/s for a fully penetrating irrigation well. Several aquifer tests at Wanbi and Karte and several town water supply wells (Harris and Barnett, 1987) have revealed a very consistent value of 3 m/day for the hydraulic conductivity of the Murray Group Limestone. The confining effect of the overlying Bookpurnong Formation and in some cases, a semi-confining marly layer within the limestone contribute to the lower values of storage coefficient in the range of 3×10^{-2} to 4×10^{-4} .

Extractions for mostly potato irrigation cause seasonal drawdowns of up to 15 m in the confined portion of the aquifer near the State border (Zone 10A) as shown in Figure 11 which also indicates that pressure levels have reached a new equilibrium at current extraction levels (apart from the influence of the millenium drought from 2007 to 2009).

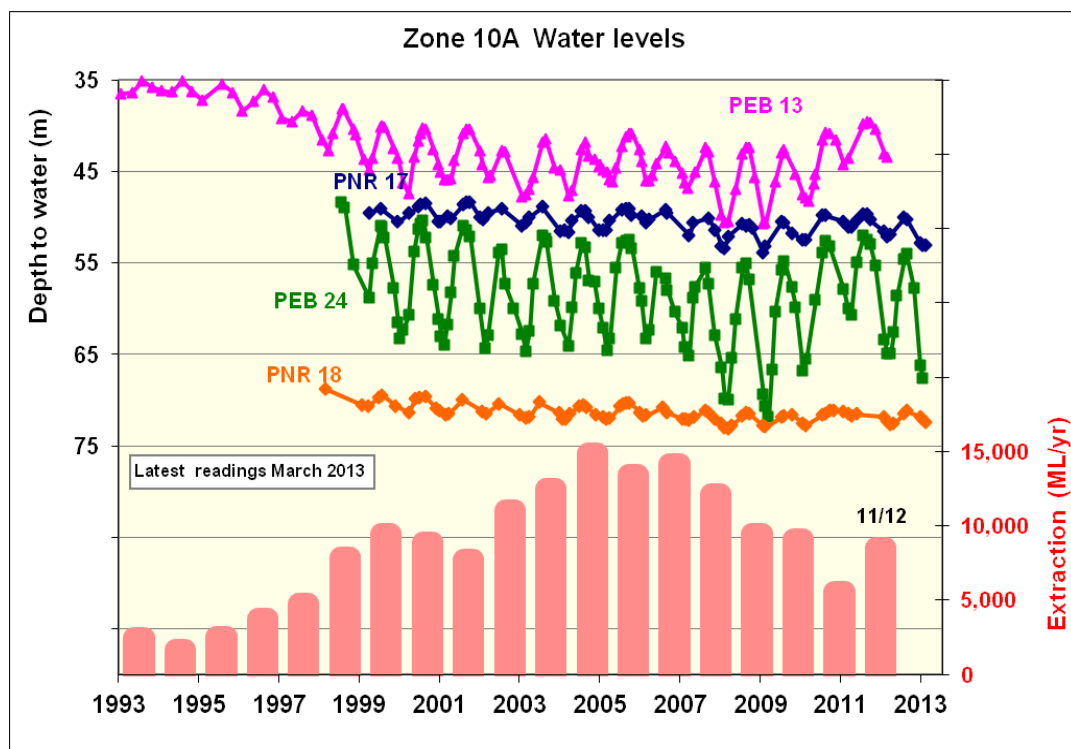


Figure 11. Pressure level hydrographs and extraction for Zone 10A where aquifer is confined

6.4 Bookpurnong Formation Confining Layer

The dark greenish grey fossiliferous clays which comprise this unit occur in the eastern half of the Mallee region and similar to the underlying units, deepen and thicken to the north (Figs. 4 and A8). It forms an effective confining layer with the majority of well records showing the first water cut at the top of the limestone aquifer and a subsequent rise in water level of several metres.

6.5 Pliocene Sands Aquifer

The watertable occurs in the Loxton - Parilla Sands only in the northeast part of the region due to downwarping across the Murrayville Fault (Fig. 4). Watertable gradients are low with groundwater flow to the north as shown in Figure 8, with salinities increasing from 4000 mg/L to over 18 000 mg/L in a northerly direction. The sharp increase in salinity is most likely due to the decrease in ground surface elevation which has allowed evaporative concentration of the groundwater during past periods of high watertables. In these areas, the salinity is much higher than the underlying confined limestone aquifer, necessitating pressure cementing of stock wells to prevent casing corrosion and leakage between aquifers (e.g. in well 7028-24, the Pliocene Sands salinity is 17 100 mg/L, whilst the limestone salinity is 6390 mg/L).

6.6 Summary

The large area of irrigation quality groundwater within the region is contained within the Mallee PWA and the Mallee WAP has set a limit for extractions and determined monitoring requirements. Apart from the low level of stock use outside the PWA where only brackish groundwater occurs, future demand may potentially arise from mining developments with heavy mineral sands the most prospective at present. Because of the deep watertable (mostly greater than 50 m below ground over most of the region), there are no known groundwater dependent ecosystems.

7 Upper Murray Region

In this region, the development of irrigation has had a significant impact on the salinity of the River Murray and floodplain by causing increased groundwater inflows. In 1993, an estimated 1 050 tonnes of salt entered the river each day between the State border and Morgan (Smith and Watkins, 1993) which would have resulted in an increase of 145 mg/L in the salinity of the river at Morgan at that time. Figure 12 shows the comparison between pre-European watertable levels and the current levels and shows the formation of watertable mounds beneath the irrigation areas which have increased saline groundwater discharge to the river and the floodplain.

The main topographic feature of the region is the River Murray whose course and valley width are structurally controlled. Between Morgan and Overland Corner, the river flows in a narrow, steep sided gorge incised into the Murray Group limestones. Upstream of Overland Corner, this consolidated limestone is downwarped and the overlying and less resistant fluvial Loxton-Parilla Sands contain the broad alluvial river valley about 10 km wide. Within both the valley and gorge sections, the alluvial silts and clays support an open woodland dominated by River Red Gum with some Black Box. Lignum and occasional Saltbush form the understorey.

Away from the river, the landscape is generally flat and gently undulating at an average elevation of 60 m with lower areas to the east below 40 m AHD. A subdued topography is provided by east-west trending sand dunes. Red-brown sandy Mallee soils predominate, and in the remaining small uncleared areas, support an open scrub of Red Mallee and Yorrell with typical arid land shrubs such as Blue-bush and Saltbush comprising the understorey.

Average annual rainfall is about 250 mm with potential evapotranspiration approximately 1500 mm/yr. There is no local surface run-off of rainfall because of the aridity, permeable soils and flat topography. The River Murray acts as a drain for all aquifer systems in the Murray Basin and consequently groundwater discharge is focussed on it. Normally these discharge rates are low because of the low hydraulic gradients resulting from the large distances from the recharge areas to the river. However as mentioned previously, the establishment of irrigation areas using river water has disturbed this equilibrium and resulted in significant impacts on river salinity and the health of the floodplain. To the north of the river, sheep grazing predominates whilst to the south, cereal cropping constitutes the main land use.

This region is characterized by a deepening of the pre-Tertiary basement in an easterly direction into a Middle Palaeozoic-Mesozoic infrabasin containing a half-graben up to 3500 m deep known as the Renmark Trough which underlies the Tertiary sediments. This trend is interrupted by the uplifted fault block along the Hamley Fault (Fig. 4). The presence of the Renmark Trough has stimulated the drilling of ten petroleum exploration wells (Thornton, 1974) with sporadic interest in further exploration continuing.

This region is relatively well known hydrogeologically due to the previous investigations carried out to address drainage and salinity problems. The earliest recorded drilling in the area commenced in 1910 with the Angas Bore drilled to the east of Loxton by Clutterbuck Bros. The Company Bore was also commenced in 1910 for the Loxton Fruit Company and was finally abandoned two years later at a depth of 550 m having found only saline water throughout the thick Tertiary sequence. Although there are no supply wells in the area due to the high salinities in all aquifers, hundreds of drainage wells have been previously drilled in various irrigation areas to prevent waterlogging caused by shallow impermeable layers.

A regional drilling program was carried out in this area in 1981/82 with results and composite logs presented in Edwards (1981a & b; 1982a). Considerably more detailed drilling and aquifer testing has been carried out all along the river from Qualco to Chowilla for the establishment of numerous interception schemes. Figure 13 displays a representative log depicting the hydrostratigraphic units and their thicknesses.

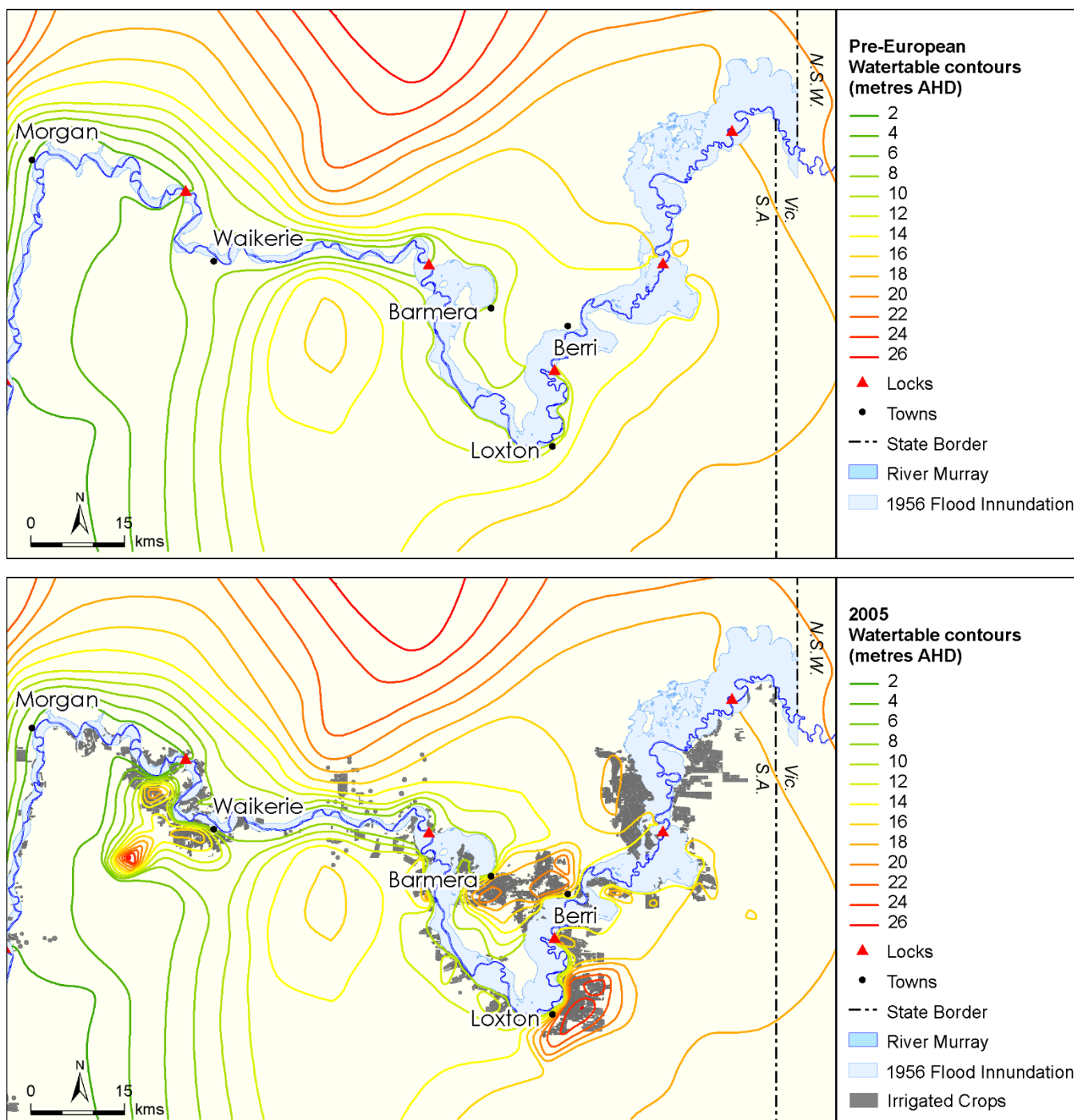


Figure 12. Comparison of pre-European and current watertable contours

7.1 Renmark Group Confined Aquifer

This aquifer is continuous over the whole region and deepens to the east to a maximum thickness of 300 m over the Renmark Trough (Fig. 4). It has been subdivided by lithology and electric log responses in petroleum wells by Thornton (1974). The Warina Sand consists of unconsolidated, fine to coarse grained quartz sands with minor thin clay and lignite beds, and is found in the deeper parts of the basin and wedges out against rising basement to the west. The overlying Olney Formation is generally much finer grained and consists of lignitic and pyritic silts and clays with interbedded sands.

Only thirteen wells provide reliable data on this aquifer in the Upper Murray Region. Most of these were drilled in 1979 as part of a regional Departmental investigation (Edwards, 1979) and intersected the Olney Formation only. An abandoned petroleum exploration well, Cooltong No. 1 drilled in 1987, was later converted to an observation well by installing 510 m of casing down

to the Warina Sand at the base of the Renmark Group. Two further wells were completed in this unit south of Renmark by the Victorian Department of Water Resources as part of its regional study of the Mallee hydrogeology (Nott, 1989). More recently, five observation wells have been completed in the Olney Formation by SA Water to monitor the confined aquifer response to pumping by the Waikerie and Woolpunda Salt Interception Schemes.

Groundwater movement, as indicated by the potentiometric surface contours (Fig. 6) is mainly to the west with inflow from the northeast and southeast. Groundwater flow is focussed on the River Murray area where it discharges by upward leakage driven by a hydraulic head difference of 15 - 20 m. Hydraulic gradients are very low as a result of the large thickness of aquifer and hence, high transmissivity. The upward leakage is the dominant mode of discharge from the confined aquifer as it thins to the west over the rising basement associated with the Hamley Fault with the overlying confining bed (Ettrick Formation) also thinning in the area. No aquifer parameters are available for this aquifer in the region, a hydraulic conductivity in the range 10-20 m/day would be expected.

Numerical groundwater flow modelling in the Woolpunda area has suggested that this upward leakage contributes significantly to the formation of a broad watertable mound on both sides of the river which results in steep watertable gradients towards the river (Fig. 12). Pressure levels in the confined aquifer are lower in the mound area than in the surrounding region which also suggests upward leakage. Hydrochemical evidence also supports this hypothesis by differentiating between two distinct populations north and south of the river. Within each population, the Murray Group limestone groundwater is hydrochemically similar to the Renmark Group groundwater (Telfer, 1991) as a result of the upward leakage.

Salinities in the Renmark Group aquifer are generally in the range 20 000 - 25 000 mg/L in the centre of the region (Fig. 6) which is the highest salinity zone for the aquifer in South Australia. Salinities increase away from the recharge areas at the basin margins, with quite a steep salinity gradient to the south. Supplies of up to 25 L/s were obtained from the deep Victorian observation wells (GDN 46 and BKP 17) completed with 7 m long screens in the Warina Sand. BKP 17 is artesian owing to the low-lying topography below 30 m AHD in the Noora-Yamba area (Barnett, 1992c).

7.2 Ettrick Formation Confining Layer

The thickness of this unit (which is continuous over the region), varies from 12 to 75 m and it exhibits similar structural undulations in the Morgan - Overland Corner area to those in the underlying units followed by deepening to the east (Fig. 4). The Ettrick Formation consists typically of grey-green glauconitic marls, and maintains a significant head difference between the underlying Renmark Group confined aquifer and the overlying Murray Group Limestone aquifer. Significant upward leakage still occurs, especially where the Ettrick Formation is thin.

A laboratory value of less than 5×10^{-7} m/day was obtained for the vertical hydraulic conductivity of a core of finely laminated silty marl taken from well MRK 18 at Woolpunda.

7.3 Murray Group Limestone Aquifer

The Murray Group Limestone follows a similar structure to the underlying units. It has an average thickness of about 100 m to the west of Overland Corner where the aquifer is unconfined, but to the east, it thickens to about 150 m at the State border and is downwarped below ground level and confined by Upper Miocene to Pliocene sediments, namely the Bookpurnong Formation (Figs. 4 and A6). The limestone aquifer shows generally good permeability and porosity throughout the area with yields of about 15 L/s being obtained from fully penetrating wells.

Figure 7 shows potentiometric contours for the Murray Group Limestone aquifer. To the east where it is confined, groundwater flow from the northeast and southeast is focused on the River Murray upstream of Overland Corner. These flows may contribute some saline inflows to the river by upward leakage through the low permeability Bookpurnong Formation beneath the river valley, especially where the river may have eroded down through this unit as is suspected in the Loxton area.

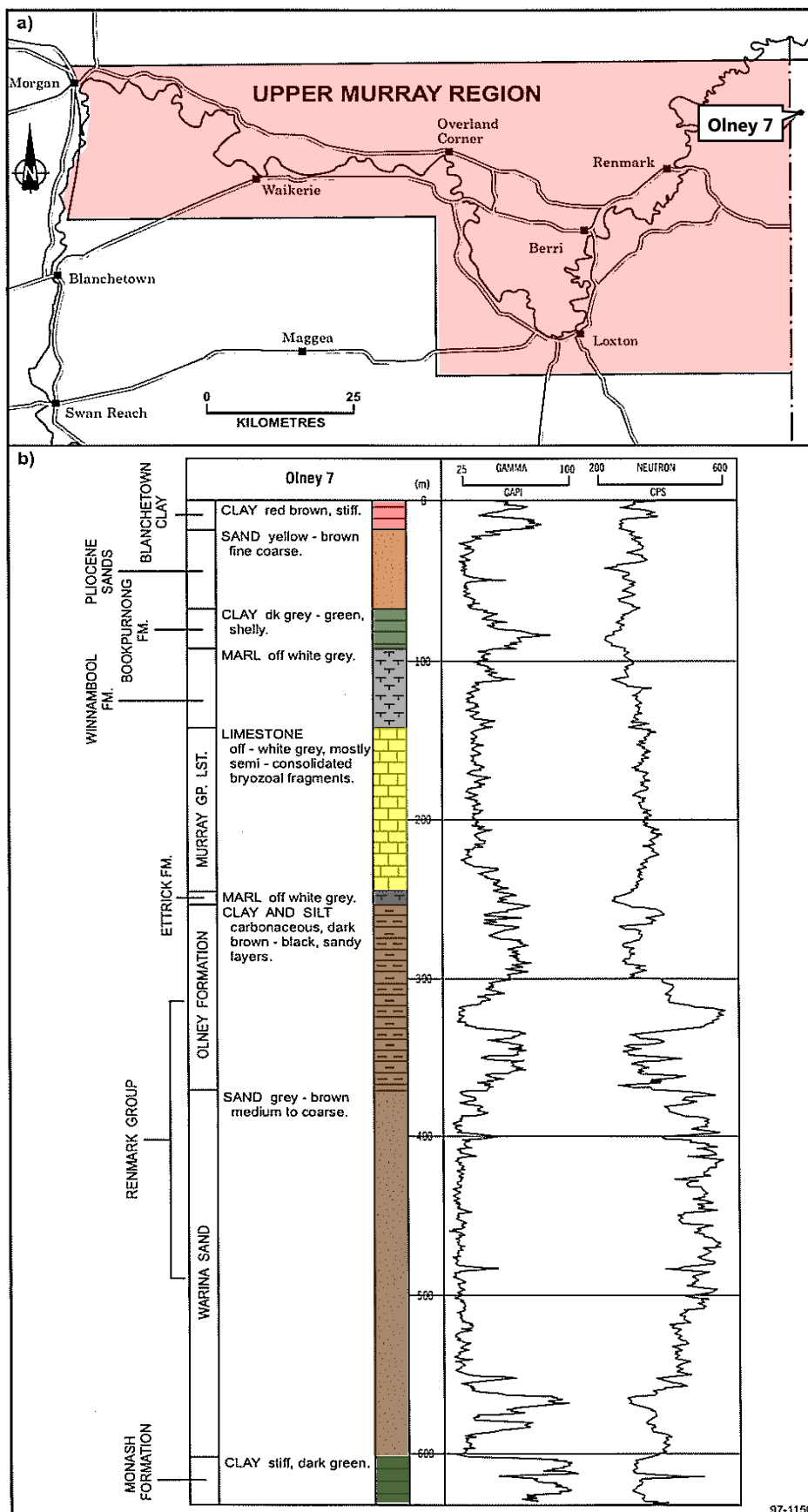


Figure 13. Upper Murray representative composite log – Olney 7

The flow patterns in the unconfined portion of the aquifer are distorted by a broad mound in the watertable which has resulted in the steep gradients toward the river from both sides between Waikerie and Overland Corner (Fig. 20). Large watertable mounds some 15 - 20 m above river level are present beneath the Waikerie, Golden Heights and Sunlands Irrigation Areas with smaller mounds existing beneath Taylorville and Cadell (Fig. 12). West of Waikerie, groundwater flow is from east to west parallel to the river. A large mound exists beneath the Stockyard Plain Disposal Basin.

The cause of the watertable mound between Waikerie and Overland Corner has been attributed primarily to upward leakage from the underlying Renmark Group confined aquifer on the basis of hydrochemistry (Telfer, 1991) and also the chemical and environmental isotopic analysis carried out by the Centre for Groundwater Studies (Herczeg et al, 1989). The resultant steep watertable gradients contributed about 200 tonnes/day of salt to the River Murray between Waikerie and Overland Corner before the establishment of the salt interception scheme.

Groundwater salinities in the Murray Group Limestone aquifer generally increase downgradient from the recharge areas, especially on the southern side of the River Murray where salinities increase to over 20 000 mg/L adjacent to the river. Further to the east where the limestone aquifer is confined, salinities also increase downgradient in a northwesterly direction to over 25 000 mg/L in the Barmera area (Fig. 7).

Of interest is an anomalous area which lies to the east of Loxton where salinities of over 50 000 mg/L were recorded from four holes which sample the confined limestone aquifer directly beneath, or immediately downgradient from, groundwater discharge zones in the overlying Pliocene Sands watertable aquifer in the Noora-Yamba area. Here, salinities of the watertable aquifer are in the range 50 000 - 90 000 mg/L. Although the measured confined limestone head is from two to six metres higher than the watertable, the heads are reversed to show a downward head difference of 1.6 m when density corrections are made. The resultant downward leakage of highly saline groundwater is the obvious cause of the anomalous salinity zone.

Barnett (1992d) shows hydrographs of confined limestone observation wells which showed a rising trend in the Loxton - Noora area. At that time, it was thought to be due to downward leakage as discussed above. However, similar trends in confined observation wells in the Berri and Renmark areas which are some distance from Noora, have led to the alternative theory of hydrostatic loading as outlined by Barnett (1995, 2008). The increased weight of water being added to the overlying unconfined aquifer by irrigation drainage water and increased recharge due to clearing, is compressing the elastic confined aquifer and increasing the hydrostatic pressure. Flood events in the river valley are known to have caused temporary rises in confined aquifer pressures in wells close to the river (Barnett, 2008).

Aquifer tests in the limestone aquifers have been mainly drainage tests in the Waikerie Irrigation Area and long term pumping tests for the Woolpunda and Waikerie Salt Interception Schemes. Reed (1980) tabulates the drainage test results where the hydraulic conductivity varied between 1 and 5 m/day with storage coefficient values in the range $1.3 - 7.3 \times 10^{-3}$. Sibenaler (1987, 1988a & b) reported on the intensive aquifer testing for the Woolpunda scheme which found consistent values of 1.5 - 2.5 m/day for the hydraulic conductivity and a specific yield of 0.02 - 0.03. In the Waikerie area, Telfer and Watkins (1990) calculated values of 1 - 2 m/day from numerous tests with storage coefficients of $2.5 - 8.0 \times 10^{-4}$ for a confined portion of the aquifer, and 0.01-0.036 for a semi-confined area.

In the Loxton area, a seven day aquifer test of the confined limestone aquifer for a preliminary investigation into the Loxton Salt Interception Scheme obtained a transmissivity value of 100 m²/day and storage coefficient values of $1.8 - 3.5 \times 10^{-4}$ (Australian Water Environments, 2002). Further extensive aquifer testing for the detailed design of the interception scheme provided clear evidence for the confined nature of the Murray Group Limestone that is effectively separated from the overlying Monoman Formation and Loxton Sands by the Bookpurnong Formation (Howles and Smith, 2005). Testing was carried out on "sub-aquifers" representing a finer stratigraphic subdivision of the Murray Group Limestone as defined by Lukasic and James (1998).

7.4 Bookpurnong Formation Confining Layer

The dark grey-brown shelly silts and clays only occur to the east of Overland Corner where they confine the limestone aquifer and attain a maximum thickness of about 35 m at the SA/Victoria border where they also reach their maximum depth (Fig. 4, A8).

Laboratory tests on core samples taken in the Noora area showed vertical conductivity values ranging from 1×10^{-2} m/day for more sandy layers, to 2×10^{-6} m/day for clay layers (Watkins, 1991). At Loxton, a value of 1×10^{-4} m/day for a silty portion of the unit was obtained (Watkins, 1992).

7.5 Pliocene Sands Aquifer

The Loxton-Parilla Sands unit comprising mostly fine to coarse sand, blankets the whole area and, like most of the underlying units, thickens to the east to a maximum of about 50 m (Fig. 4).

It contains the watertable aquifer to the east of Overland Corner, where it forms most of the exposures in river cliff sections. Elsewhere, the sands are elevated above the watertable, with the local exceptions of the Cadell and Waikerie Irrigation Areas, where they contain perched groundwater from irrigation drainage. Groundwater movement is toward the river from both north and south under very low gradients (Fig. 8). Discharge occurs to the river and/or billabongs or more significantly, by evaporative discharge from the floodplain (Barnett, 1990).

Local variations in the regional trends of groundwater movement are caused by watertable mounds beneath the Berri-Barmera and Loxton Irrigation Areas and a depression in the watertable due to groundwater discharge by evaporation in the low-lying Noora area (Figs. 8 and 12).

Salinities in the Pliocene Sands watertable aquifer are generally very high due to the concentration of atmospheric salts of oceanic origin by evaporation. Values range from 30 000 - 90 000 mg/L (Fig. 8) with the values over 35 000 mg/L associated with subdued topography below 40m AHD.

Aquifer tests in the Noora area obtained hydraulic conductivity values of 2 - 5 m/day for the coarser grained Pliocene Sands aquifer (Williams, 1976) with an average of 0.5 m/day for the finer grained silty portion of the aquifer. In the Chowilla dam site area, a value of 4.3 m/day was derived (Boucaut, 1967). Storage coefficients from both areas were in the range 1.5×10^{-2} to 1.3×10^{-3} . Falling head permeability tests in the Berri East area obtained a range of 0.5 - 2.5 m/day from fine grained aquifer material with 2 - 6 m/day from coarser material (Howles, 1986). Further testing in the Noora area by Watkins (1991) resulted in values of 3 - 20 m/day with a storage coefficient of 8×10^{-3} to 7×10^{-4} . Good consistency in the above results is evident.

Extensive aquifer testing for the detailed design of the interception scheme (Howles and Smith, 2005) determined transmissivity values of 100–300 m²/day, and a hydraulic conductivity in the range of 20–50 m/day, with the higher values likely to be related to the existence of coarse sands in some of the wells. Specific yield values could not be adequately determined from any of the tests.

Evaporative discharge from the gypsum flat depressions in the Noora area has resulted in a shallow cone of depression of 1.5 to 2 metres in the regional watertable. These groundwater discharge complexes also occur in the topographic 'lows' in southwestern NSW and northwestern Victoria. In particular, the active salinas of the Pink Lakes and Raak Boinkas in the Mallee region of Victoria are well documented (Macumber, 1991).

7.6 Summary

The major issue in the Riverland is the effect irrigation of highland areas adjacent to the floodplain is having on river salinity and floodplain degradation because of the high connectivity of the naturally saline groundwater with the River Murray. Extensive investigations and investments have taken place over the past 20 – 30 years to mitigate these impacts by either treating the cause of the problem (more efficient irrigation practices, rehabilitation of the water distribution systems), or treating the symptoms (salt interception schemes).

8 Northern Region

The northern region of the Murray Basin comprises a gently undulating plain rising gradually in elevation from about 45 m AHD near the River Murray, to about 170 m where it abuts the Mount Lofty/Olary Ranges which sweep in an arc from west to north. Widespread easterly trending sand dunes covered with open Mallee scrub, together with occasional large claypans which support a Bluebush and Black Oak cover, are the main topographic features. On the margins adjacent to the highlands, extensive floodouts and occasional low-angle coalescing alluvial fans occur. Ephemeral creeks (such as Olary and Manunda Creeks) discharge onto the plains for a distance of 20 - 30 km before all of the flow infiltrates into the permeable sediments.

Mean annual rainfall varies between 150 - 250 mm. Most of the area is devoid of surface runoff due to the sandy nature of the soils except near the basin margin where heavy localized downpours produce flows in the ephemeral creeks and floodouts. A widespread network of surface drains harvests much of these flows for large dams which are important sources of water for sheep grazing, the dominant land use. Most of the area remains under natural vegetation because the rainfall is too low and unreliable for crop production. The establishment of the Bookmark Biosphere Reserve, (which incorporates Chowilla Regional Reserve, Dangali Conservation Park and Calperum Station) covers some 5700 kms², and preserves vegetation cover over a third of the region (Fig. 2).

Investigations on a basin-wide scale (Brown and Stephenson, 1991) have revealed that the northern region encompasses an area of significant facies variations which reflect the transition from shallow marine platform conditions in the south, to marginal marine and tidal flat zones to the north. This is represented by a change in lithology from Murray Group Limestone to glauconitic marls of the Winnambool Formation to the black carbonaceous Geera Clay.

A Departmental drilling programme was carried out in 1982 which, together with a wide overview of the basin as a whole, enabled the sediments to be correlated with defined Tertiary units elsewhere in the Murray Basin. Drilling results and composite logs from the drilling programme are presented in Edwards (1982a, b). Reinterpretation of these logs in the light of the basin-wide approach has resulted in changes to the stratigraphic subdivisions made in these early reports.

The drilling and levelling programme enabled structure contours to be drawn of the various units (Appendix A) and cross-sections to be constructed (Fig. 4). These show that all of the Tertiary units as well as the pre-Tertiary basement, deepen towards the southeast of the region which is the deepest part of the Murray Basin as a whole.

8.1 Renmark Group Confined Aquifer

This unit occurs over most of the region and wedges out against rising basement to the north and west. The structure of the Renmark Group reflects that of the underlying basement i.e deepening to the southeast. It also thickens in this direction, from several metres at the margins to over 300 m in the Chowilla area (Fig. A4). Most of the drilling program encountered glauconitic and pyritic, medium grained shelly sands above carbonaceous material normally associated with upper Renmark Group (Olney Formation). Several of the wells drilled some sixty years ago reported 'drift sand' at this level.

Potentiometric contours (Fig. 6) show a very low gradient toward the southwest which suggests either a high transmissivity for the confined aquifer or a low rate of recharge or both. No aquifer parameters are available for this aquifer which appears to be recharged from the elevated basin margins further to the east. Although present recharge rates are very low due to the prevailing semi-arid climatic conditions, they would have been higher during the wetter periods of the Plio-Pleistocene.

Groundwater salinities are lower near the basin margins (Fig. 6), increasing from 8000 mg/L to over 15 000 mg/L to the southeast. The marginal salinities themselves increase in a northerly direction (from about 8000 mg/L north of Morgan to over 11 500 mg/L south of 'Muturoo' which probably reflects decreasing rainfall and hence, decreasing recharge which may occur laterally from the basement rocks.

Canegrass Bore (well 7030-4) flowed at about 2.5 L/sec when first drilled in 1927 with a strong odour of hydrogen sulphide (Fig. 14). The head was initially 5.5 m above ground, but the well ceased to be artesian some 20 years later.

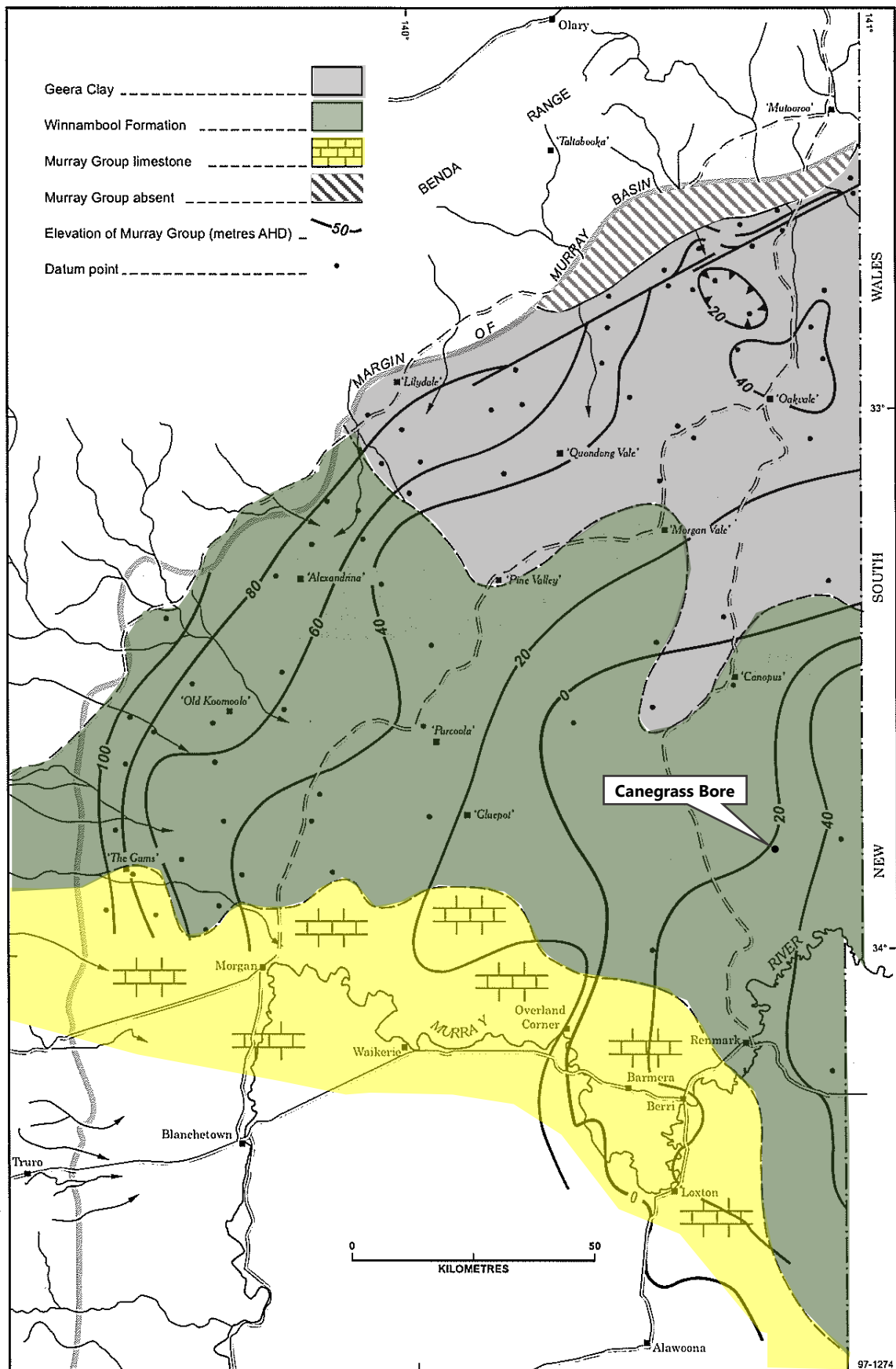


Figure 14. Structure contours of the top surface of the Winnambool Formation / Geera Clay

8.2 Winnambool Formation/Geera Clay Confining Layers

As mentioned previously, these units are the lateral time equivalents of the marine Murray Group Limestone. The Winnambool Formation occurs as a grey-green fossiliferous marl which laterally grades into the black to grey carbonaceous Geera Clay, both of Oligo-Miocene age. The top surface of these deepens steadily to the southeast (Fig. 14).

Although these units are generally considered aquicludes, shelly layers and sand lenses form local aquifers which yield small supplies of mostly unusable water. Salinities range from 12 000 to 20 000 mg/L with occasional values of up to 24 500 mg/L. Values generally decrease toward the basin margin reflecting the recharge effects from run-off.

8.3 Murray Group Limestone Aquifer

This aquifer occurs only in the southern half of the region and is confined by the overlying Bookpurnong Formation (where it occurs) or interdigitating low permeability marls of the Winnambool Formation (Fig. 4).

The groundwater salinity distribution is similar to the Winnambool/Geera confining layer with a general range of values from 10 000 - 16 000 mg/L and a trend of increasing salinity toward the south (Fig. 7). An area of very high salinity exists to the north of Waikerie with values of over 30 000 mg/L. Potentiometric heads (Fig. 7) show a southerly groundwater movement under a low gradient. Heads are generally higher than water levels in the overlying watertable aquifer by up to 11 m but are lower than the underlying Renmark Group confined aquifer, especially in the southern part of the region. This trend of increasing head with depth emphasize this area as a regional discharge zone through upward leakage from deeper aquifers, with the salinity distribution in the limestone aquifer providing even further evidence for upward leakage because of its similarity with the underlying Renmark Group confined aquifer.

At its northern-most extent, the limestone aquifer is also at its thinnest as it wedges out against the lower permeability units. The salinities of about 11 000 mg/L are lower than the adjacent Winnambool - Geera confining layer and are similar to the underlying confined aquifer. To the south, the previously mentioned anomalous zone of salinity greater than 30 000 mg/L occurs in an area where there is significant connection with the overlying saline Pliocene Sands aquifer in the absence of the intervening confining layer.

8.4 Pliocene Sands Aquifer

This fluvial and estuarine unit is extensive and blankets most of the region. It ranges in thickness from 20 to 50 m (Fig. 4) and comprises fine to coarse (sometimes gravelly), moderately well sorted quartz sands, yellow-brown to grey in colour with occasional clay interbeds.

The watertable lies within the Loxton-Parilla Sands over most of the region except where the sands are elevated above the zone of saturation towards the north and west. Information is scarce on this aquifer because its high salinity did not encourage drilling and sampling. Watertable contours (Fig. 8) show groundwater flow to the south under very low gradients.

Groundwater salinities vary greatly, from below 3000 mg/L in the western recharge areas of Burra and Newikie Creeks, to over 35 000 mg/L in areas of low topography to the north of Renmark (Fig. 8). There appears to be a general trend of increasing salinity towards the south. No aquifer parameters are available in this area from tests, but an estimate of 5 m/day for the hydraulic conductivity would be reasonable.

8.5 Summary

Because of high salinity over large areas, utilization of groundwater is very low. The low rainfall has resulted in virtually no large scale clearing of native vegetation for cropping and consequently, there has been no major change in the hydrological balance. Future demand may potentially arise from mining developments with heavy mineral sands the most prospective at present. Because of the deep watertable (mostly greater than 40 m below ground over most of the region), there are no known groundwater dependent ecosystems.

9 Western Margin

The western margin of the Murray Basin lies between the River Murray and the Mount Lofty Ranges from Lake Alexandrina in the south to Morgan in the north. Tectonism and the resulting undulating and often shallow basement have resulted in condensed geological sequences and sometimes poorly developed aquifers. Groundwater supplies and salinities are consequently quite variable.

The Ranges exert a strong rain shadow effect with a decrease in annual rainfall from 350 mm in the highlands to about 230 mm on the plains (Fig. 2).

The soils on the uplifted fault block associated with the Morgan Fault are stony and skeletal, directly overlying calcrete. Consequently, the area is still largely under native Mallee vegetation. The narrow calcrete plain between the prominent eastern scarp of the Morgan Fault and the River Murray has been downthrown 50 m and is mostly cleared and used for sheep grazing. Elsewhere toward the Ranges, the soil cover is thicker with sandy loam over clay predominant and cereal cropping the main land use (Fig. 2).

The western margin to the north of Mannum is underlain by the Cambrai Block, an uplifted fault block of crystalline rocks which is part of the Mount Lofty Ranges structural horst but is marginal to the topographic highland (Twidale, Lindsay and Bourne, 1978). Bounded to the east by the Morgan Fault, the Cambrai Block is covered by a thin Cainozoic sequence of less than 100 m and is also responsible for the southerly diversion of the River Murray at Morgan (Fig. A2).

The western margin of the Murray Basin is fault controlled for the most part, providing a sharp contact between the basin sediments and the Mount Lofty Ranges. However, to the north of the Sturt Highway, the boundary is much less distinct with sediments onlapping a sloping basement floor. Resurgent tectonics has transmitted basement structures up through the Cainozoic sediments to the ground surface. On-going movement of the fault blocks during the Tertiary is evident from the hydrogeological cross-section (Fig. 4).

9.1 Renmark Group Confined Aquifer

This aquifer is restricted in its areal extent because of the undulating nature of the underlying bedrock. Few private wells penetrate this aquifer because of its unreliable yields and better prospects in the overlying limestone aquifer. Exploration drilling for brown coal has provided useful information on the Renmark Group, mainly from a stratigraphic viewpoint. Most of the hydrogeological information has been obtained from the Departmental drilling programme (Barnett, 1988a & b).

The discontinuous nature of the aquifer is emphasized in Figure A4 as well as the hydrogeological cross-section (Fig. 4) which also show a deepening of the unit to the east with some major modifications due to block faulting. The glauconitic shelly sands of the Compton Conglomerate are included as part of the Renmark Group confined aquifer. Groundwater movement is eastwards from the basin margins towards the River Murray (Fig. 6). Recharge appears to occur laterally from the basement rocks of the Mt Lofty Ranges along the faulted basin margin, rather than down through the unconfined limestone aquifer. The positive hydraulic head difference of about two metres measured near the margin, indicates discharge by upward leakage into the Murray Group Limestone aquifer.

Groundwater salinity contours (Fig. 6) show a general trend of increasing salinity away from the recharge areas at the margins, with a similar increasing trend from south to north, probably reflecting the increase in salinity of recharging basement groundwater in that direction. Stock quality water exists to the west of Morgan but further to the south, much higher salinities (over 20 000 mg/L) are obtained, probably due to restricted flow as a result of shallow basement. Salinities are much lower south of Sedan due to the higher recharge from higher rainfall.

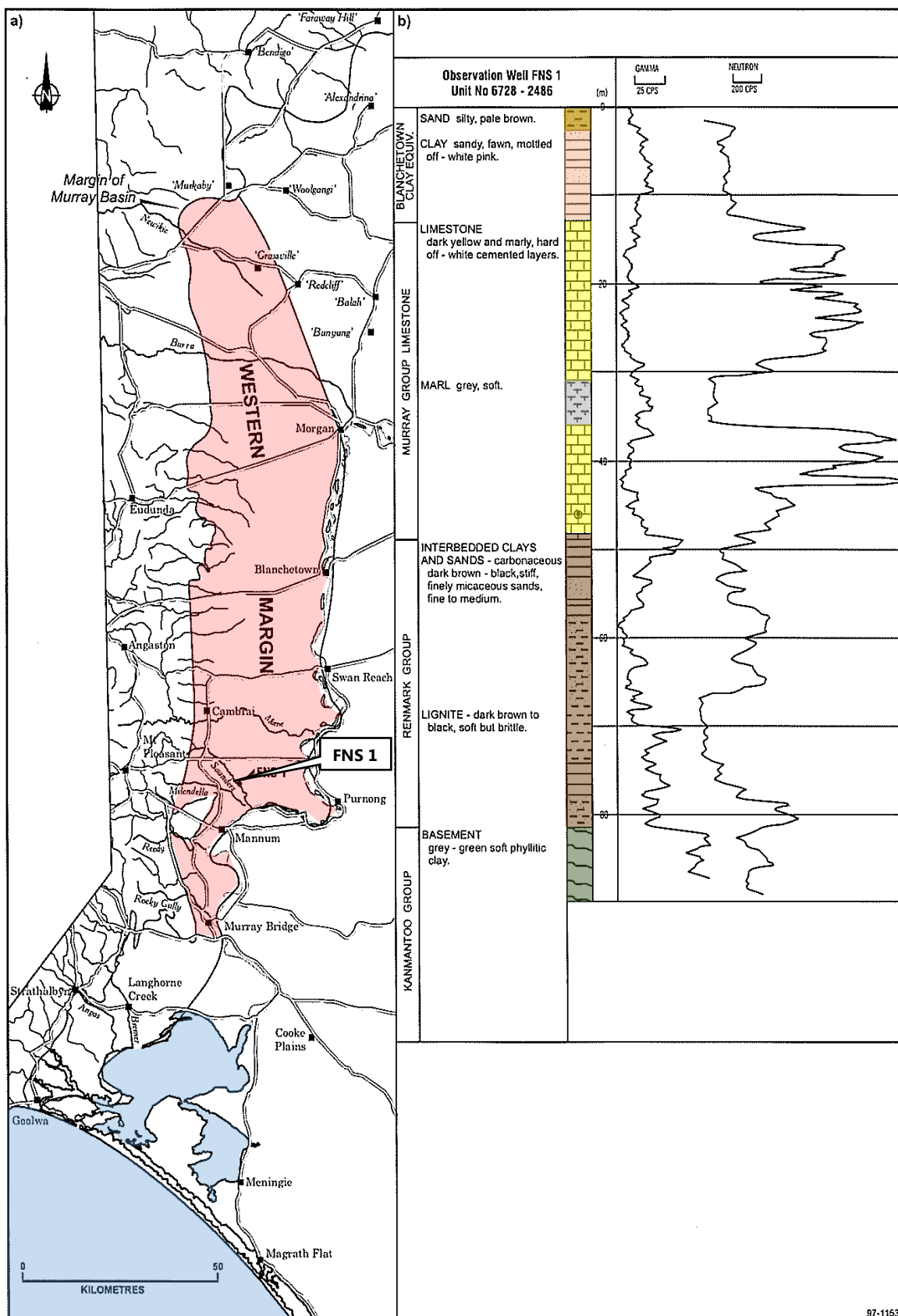


Figure 15. Western Margin representative composite log – FNS 1

9.2 Murray Group Limestone Aquifer

Except where it is elevated above the zone of saturation, the Murray Group Limestone forms the watertable aquifer over most of the region. These areas of uplift occur along the basin margins to the north in the Bower area and on the flanks of granite inselbergs near Sedan and Mannum. The limestone aquifer is used for stock and domestic purposes in the southern portion of the region where salinities are low. The saturated thickness generally increases toward the east except where block faulting has thinned the aquifer (Fig 4).

Groundwater flows from the basin margins eastwards towards the River Murray valley (Fig. 7) where discharge occurs to the river and/or billabongs but mostly by evaporative discharge from the floodplain. The watertable contours show some interesting features. Between Blanchetown and the Marne River, a steep gradient zone is associated with the Morgan Fault. This is because the uplifted fault block has created a barrier to the eastward flow of groundwater. Another example exists near the confluence of the Marne and Murray Rivers near Walker Flat. Here, groundwater is held at an elevation of 40 m AHD only 2.3 km from the River Murray whose pool level is 0.75 m AHD. The Morgan Fault is thought to pass between the two areas.

There appears to be evidence for enhanced localized recharge along the uplifted Morgan Fault block near Blanchetown and Swan Reach. The sparsely vegetated area is covered with thin soils with broad depressions in the limestone surface indicating possible solution activity. Small watertable mounds exist, with an associated area of lower salinity (Fig. A13) to the west of Blanchetown. Numerous wombat burrows also probably assist localised recharge.

Elsewhere along the western margin, recharge is lower as indicated by the higher groundwater salinities to the north and south. This is most likely the result of decreased surface flows which have a higher salinity. Stock quality water is found over most of the region with the exception of the area to the northwest of Blanchetown where an unusually high salinity of 51 812 mg/L was found in the Murray Group Limestone aquifer (Fig. 7) and it is significant that it is downgradient from the low-lying Craigie Plains area which was quarried for gypsum. This indicates that evaporative discharge from the watertable possibly took place when it was 15 m higher than its present level, probably during the Pliocene era. The high groundwater salinity probably results from this process.

9.3 Pliocene Sands Aquifer

The Loxton - Parilla Sands only contain groundwater in the northernmost part of the region in the vicinity of Burra and Newikie Creeks. The sand aquifer averages 5 - 10 m in thickness and directly overlies the grey marls of the Winnambool Formation. It is recharged by intermittent flows in creeks with groundwater flow to the east. Groundwater salinities are in the range of 2000 - 7000 mg/L which has led to development for stock use.

9.4 Summary

Because of the generally high groundwater salinities and low yields, there is limited potential for groundwater development. There is no evidence of rising watertables resulting from vegetation clearance or highland irrigation which could adversely affect the River Murray salinity in the future.

10 Coastal Plain Region

The Coastal Plain lies on the southwestern margin of the Murray Basin (Fig. 16). Because of this, it has a much more complex sedimentary history than elsewhere in the basin, ranging from Permian glaciations to several marine transgressions, all occurring on an undulating basement surface. Perhaps the most significant geological event in shaping today's landscape and also human interaction with it, was the Pleistocene marine transgression which occurred about one million years ago. It eroded away much of the older Tertiary sands and limestones and left a broad, flat low-lying area which gave rise to its description as the Coastal Plain.

The low elevation of this area is a major factor in the widespread occurrence of dryland salinisation which is caused by human interference in a delicate hydrological balance by the clearing of deep-rooted native vegetation.

The Coastal Plain varies from flat calccrete plains with a veneer of sandy soils and sometimes discontinuous east-west sand dunes, to broad sand covered stranded beach ridges. Most of this area has been cleared for grazing or cereal cropping (Fig. 2), although significant areas of Mallee scrubland and heath remain on the isolated granite inselbergs (such as Mount Boothby and Binnie Lookout) which rise to about 150 m AHD. Lakes Alexandrina and Albert are the termination of the River Murray and are separated from the Coorong and the Southern Ocean by a series of barrages which were completed in 1940. These barrages prevent inflow of sea water during low river flow and maintains a stable water level in the lakes of about 0.75 m AHD. Low-lying samphire swamps and salt lakes surround the lakes.

Annual rainfall varies from about 500 mm in the south to just over 400 mm in the north. Because of the predominantly sandy soils with high permeability, there is negligible surface drainage. Ancient drainage lines can be seen on areas of high relief, such as Binnie Lookout and the Marmon Jabuk Range, but any flows would only result from heavy localized storms.

The Coastal Plain straddles the major structural feature of the area, the Padthaway Ridge which forms a NW-SE trending basement high (Figs. A1, A2). As mentioned previously, outcropping Ordovician granite forms inselbergs which rise above the plain. The Kanmantoo Group of Cambrian age is also prominent and consists of metamorphosed quartz-mica schists, metasilstones and occasional basic igneous rocks (Rogers, 1980). Permian sediments consisting of mainly blue-grey clays with occasional fine grained sandy intervals have also been intersected in Departmental drilling (Barnett, 1992a). The Pleistocene marine transgressive extended as far inland as the Marmon Jabuk Scarp and deposited shallow marine limestones of the Coomandook Formation and also beach and coastal dune deposits of Bridgewater Formation (Rogers, 1980). Black organic clays of the St Kilda Formation were deposited in low-lying areas around the lakes when they expanded in response to a higher sea level about 6000 years ago.

Because the Buccleuch Formation intercalates with and sometimes overlies the Renmark Group, they are considered interconnected and part of the same Renmark Group confined aquifer system. The shallow marine limestones deposited during the Pleistocene are collectively known as the Quaternary Limestone aquifer. They overlie and are often difficult to distinguish from the older Murray Group Limestone aquifer because of the high degree of reworking, and are consequently treated as the one unconfined aquifer system which has very good interconnection.

Monitoring began in this region in 1983 with an observation well network established around Tintinara to monitor the effects of irrigation from the unconfined Quaternary limestone aquifer. Ironically, the groundwater levels showed a rising trend in response to the clearing of native vegetation and the relatively shallow depth to the watertable, and alerted researchers to the presence of the dryland salinity problem on the Coastal Plain. An extensive network is now monitoring the Quaternary Limestone aquifer throughout the Coastal Plain area and although widespread rising trends were recorded in the past (Barnett, 1997), below average rainfall since 2000 has resulted in declining water levels and a much reduced risk of dryland salinity.

Although there was a large amount of information from private wells in the shallow Quaternary Limestone aquifer, there was very little in saline areas of the Renmark Group confined aquifer, mainly toward the coast and the lakes. Consequently a drilling programme was carried out with the multiple objectives of obtaining sedimentary core for palaeontological analysis, basement core and the construction of observation wells in the confined aquifer (Barnett, 1992a).

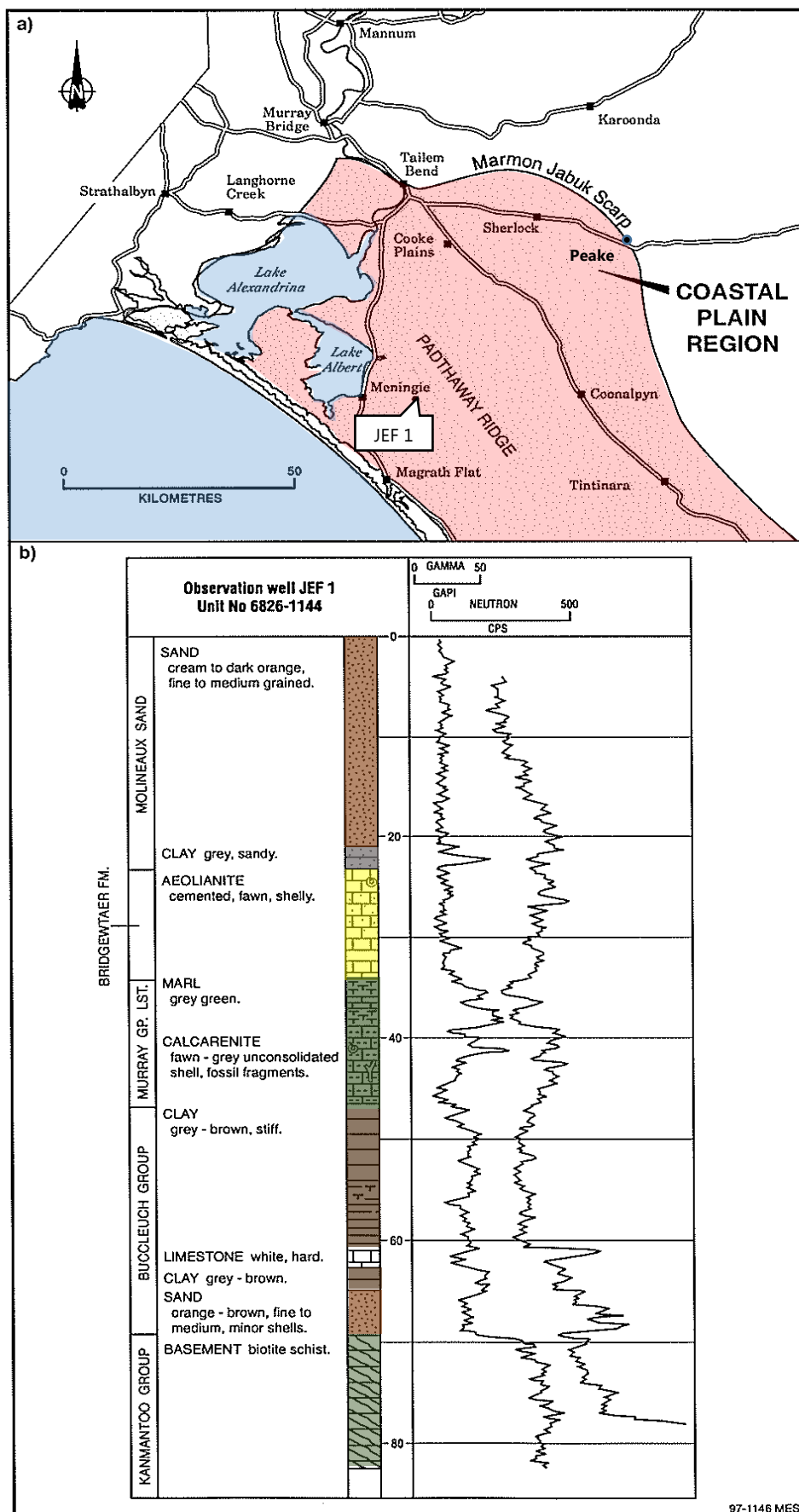


Figure 16. Coastal Plain representative composite log – JEF 1

10.1 Renmark Group Confined Aquifer

The confined aquifer comprises both the Buccleuch Group and the underlying Renmark Group where it occurs. Many stock and some irrigation bores were drilled down to the confined aquifer in the northeast part of the Coastal Plain (the Coomandook, Sherlock, Peake area) because of the very high salinities in the overlying unconfined aquifer. Unfortunately, when they were drilled in the 1940's and 1950's, the casing was not pressure cemented and many have now been abandoned due to corrosion of the steel casing by the saline watertable.

Groundwater movement in the confined aquifer is from east to west along a flow path from recharge areas in southwest Victoria as shown in Figure 6, which also displays salinities, with a relatively rapid increase in salinity towards the west probably as a result of stagnating groundwater flow against the rising basement of the Padthaway Ridge.

The main aquifer zones within the Buccleuch Group are unconsolidated sand-size bryozoal fragments (known as "bryozoal sand" in the early geological logs) and consolidated bryozoal limestone or "coral". Quartz sand layers form the aquifers in the Renmark Group which underlies the Buccleuch Group. The main confining layer over most of the area is the uppermost black lignitic clay because the Ettrick Formation (glauconitic grey-green marl) which acts as the confining layer elsewhere in the basin, is often absent. Data on the confined aquifer to the west of the Coastal Plain is sparse due to the high salinities, and more importantly, because it may not exist over areas of shallow basement (Padthaway Ridge) between Taillem Bend and Meningie.

A hydraulic head difference between the confined and unconfined aquifer of about +1 to +2 metres indicates upward leakage, which is hardly surprising as this is the only available mechanism for discharge from the confined aquifer. Lateral discharge to the Southern Ocean is largely impeded by the Padthaway Ridge. Long term monitoring shows confined aquifer pressure level trends beneath the Coastal Plain follow those in the overlying unconfined aquifer due to process of hydrostatic loading which has been discussed earlier in this report (Barnett, 1995 & 2008).

The Moorlands Lignite Member occurs in the upper Renmark Group and has been subject to lignite exploration since 1910 in the Moorlands Coalfield, 20 km east of Taillem Bend on the flanks of the Padthaway Ridge. As part of the latest investigation to determine the potential of the deposit as a fuel for cement manufacture by Adelaide Brighton Cement, an aquifer test on the sands of the Buccleuch Group overlying the lignite was carried out (Coffey and Partners, 1982). A value of 5 m/day was obtained with a storage coefficient averaging 0.007. This is the only aquifer test carried out on the Renmark Group in the region.

Intensive irrigation using the confined aquifer commenced relatively recently in 2004 on the northeastern margin of the Coastal Plain adjacent to the town of Peake (Fig. 16). Here, a combination of arable soils, acceptable salinity (<1500 mg/L) and economic depth (~100 m), led to the extraction of about 1200 ML/yr from both the Buccleuch and Renmark Group aquifers which were not prescribed at the time. Figure 17 shows the dramatic impact of the extraction on pressure levels which was of concern to local dryland farmers and necessitated the lowering and upgrading of pumps providing stock and domestic supplies. The Peake-Roby-Sherlock Prescribed Wells Area came into being, and a hydrogeological investigation (Barnett and Yan, 2008) informed the subsequent Water Allocation Plan which sets limits for groundwater extraction.

10.2 Ettrick Formation Confining Layer

The grey-green marls of the Ettrick Formation are absent over most of the region because of the complex erosion and depositional history during the late Eocene to late Oligocene period. It is found on the eastern margins of the Buccleuch Embayment toward the Murray Basin proper.

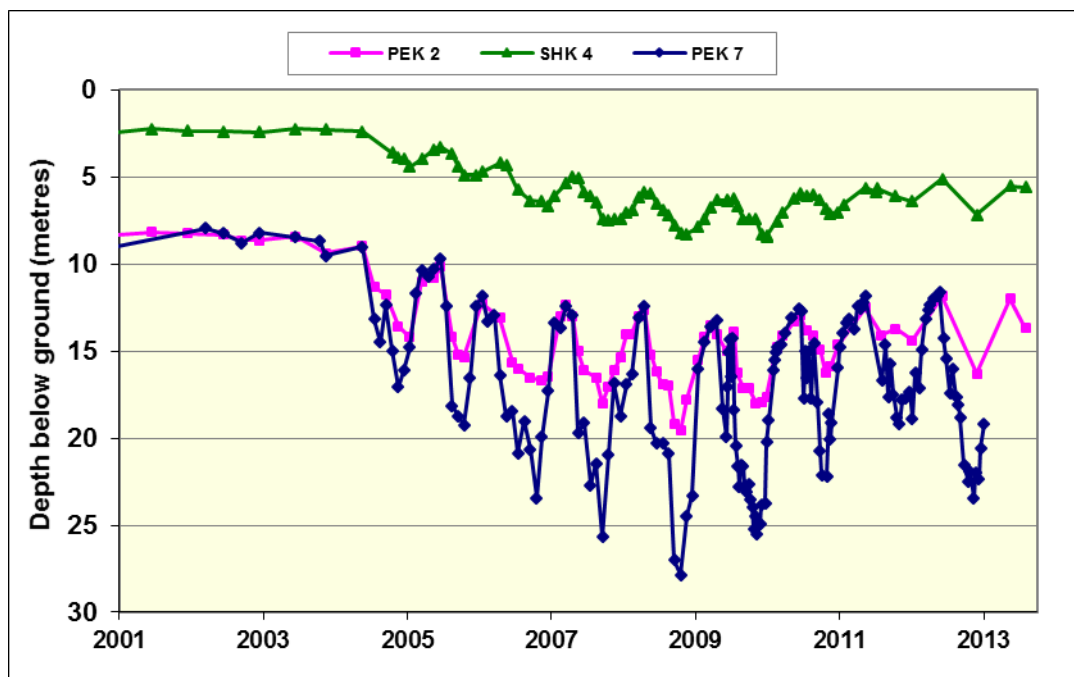


Figure 17. Pressure level hydrographs in the Peake-Roby-Sherlock PWA

10.3 Quaternary Limestone/Murray Group Limestone Aquifer

The watertable lies within several Quaternary units, the most widespread being the Coomandook Formation and the Bridgewater Formation and occasionally the overlying Molineaux Sand (Fig. A9). The sandy limestones which make up these units are very similar to the underlying Murray Group Limestone, there is no evidence of any low permeability unit separating them, and consequently all are considered to comprise the unconfined aquifer.

Groundwater movement is from east to west under a very low hydraulic gradient which reflects the high permeability of the aquifer. The long flow-path of about 250 km originates in the high rainfall area of southwest Victoria. Figure 7 shows the watertable contours for the unconfined aquifer.

The groundwater salinity distribution (Fig. 7) shows some interesting features which strongly reflect the local geology and also the extent of the Pleistocene marine transgression. Low salinity groundwater is found along the eastern margins of the Coastal Plain bordering the Mallee Region with a general increase in salinity toward the west. These low salinity zones are formed by westward movement of fresh groundwater downgradient from beneath the Mallee.

Areas of low salinity (less than 3 000 mg/L) are also found in areas of enhanced recharge. This occurs adjacent to the impermeable granite inselbergs where there is evidence of watertable mounding in nearby wells. The other area of low salinity occurs immediately to the south of Tailem Bend where enhanced recharge through solution features has occurred after rainwater collects in depressions in the calcreted surface (probably after extreme events).

Another small area exists eight kilometres east of Tailem Bend at Elwomple where a shallow depression in calcrete of relatively large magnitude collects rainwater which infiltrates and results in groundwater salinities of 1 500 - 3 000 mg/L. A trench was dug in 1939 to intercept the good quality groundwater which was reticulated to surrounding landowners several kilometres away. This extensive development of Bakara Calcrete on top of the Quaternary limestones has necessitated the drilling of numerous drainage wells in the Tailem Bend and Coonalpyn townships to provide drainage for septic tank effluent.

Areas of deep sand, (ie Molineaux Sand) overlying Bridgewater Formation, allow above average diffuse recharge resulting in salinities between 3000 - 7000 mg/L over significant areas, however salinity values may increase with depth. Barnett (1997) summarizes TEM surveys carried out in the Meningie - Narrung area to delineate areas of stock quality groundwater to be used in the event of blue-green algae outbreaks in the lakes.

High salinities of over 35 000 mg/L are associated with evaporative concentration in low-lying groundwater discharge areas. In fact, a salinity of 190 000 mg/L was recorded beneath a salina in the Cooke Plains embayment, two kilometres southwest of the railway siding at Cooke Plains. These discharge areas have a pronounced effect on the watertable contours to the west of Coomandook and near this embayment. Watertable elevations at discharge areas adjacent to Lakes Alexandrina and Albert, after being corrected for density effects, are often below sea level and are consequently the focus for regional groundwater discharge in preference to the lakes which are held at +0.75 m AHD (Fig. 18). These low lying discharge areas also occur further south adjacent to the Coorong, although the consequence of groundwater discharge to the Coorong is insignificant due to its high salinity.

A 70 hour aquifer test carried out at the Centre for Groundwater Studies site at Cooke Plains obtained hydraulic conductivity values in the range 15-20 m/day with a specific yield of 0.05. Calculations of groundwater velocity result in values of 10-15 m/year (Barnett, 1992c).

The area of high groundwater salinity (over 14 000 mg/L) along the eastern margin of the Coastal Plain is difficult to explain. It lies between Tailm Bend and Tintinara and also between the Padthaway Ridge and the Marmon Jabuk Scarp. The landscape is generally flat and underlain by calcrete, with the permeable sands of the Bridgewater Formation and Molineaux Sands mostly absent. The fact that the steep salinity gradient coincides the maximum extent of the marine transgression would suggest that the high salinities could be due to connate water which has been subsequently diluted by recharge.

10.4 Summary

All areas of useable groundwater below 3000 mg/L in both confined and unconfined aquifers on the Coastal Plain are within the Peake-Roby-Sherlock Prescribed Wells Area. The Water Allocation Plan has set extraction limits and identified there are no risks to groundwater dependent ecosystems from extractions in this area.

Regional discharge of naturally saline groundwater occurs predominantly to low-lying saline areas which mostly surround and protect the fresh water contained within Lakes Alexandrina and Albert.

Earlier concerns about dryland salinity caused by the rising regional watertable in the early 1990s has declined due to below average rainfall since 2000 which has resulted in generally declining water levels. Another potential area of concern is the possible contamination of the low salinity Renmark Group confined aquifer by leakage from the saline watertable through abandoned wells with corroded steel casing. However the area where downward leakage can occur is relatively small.

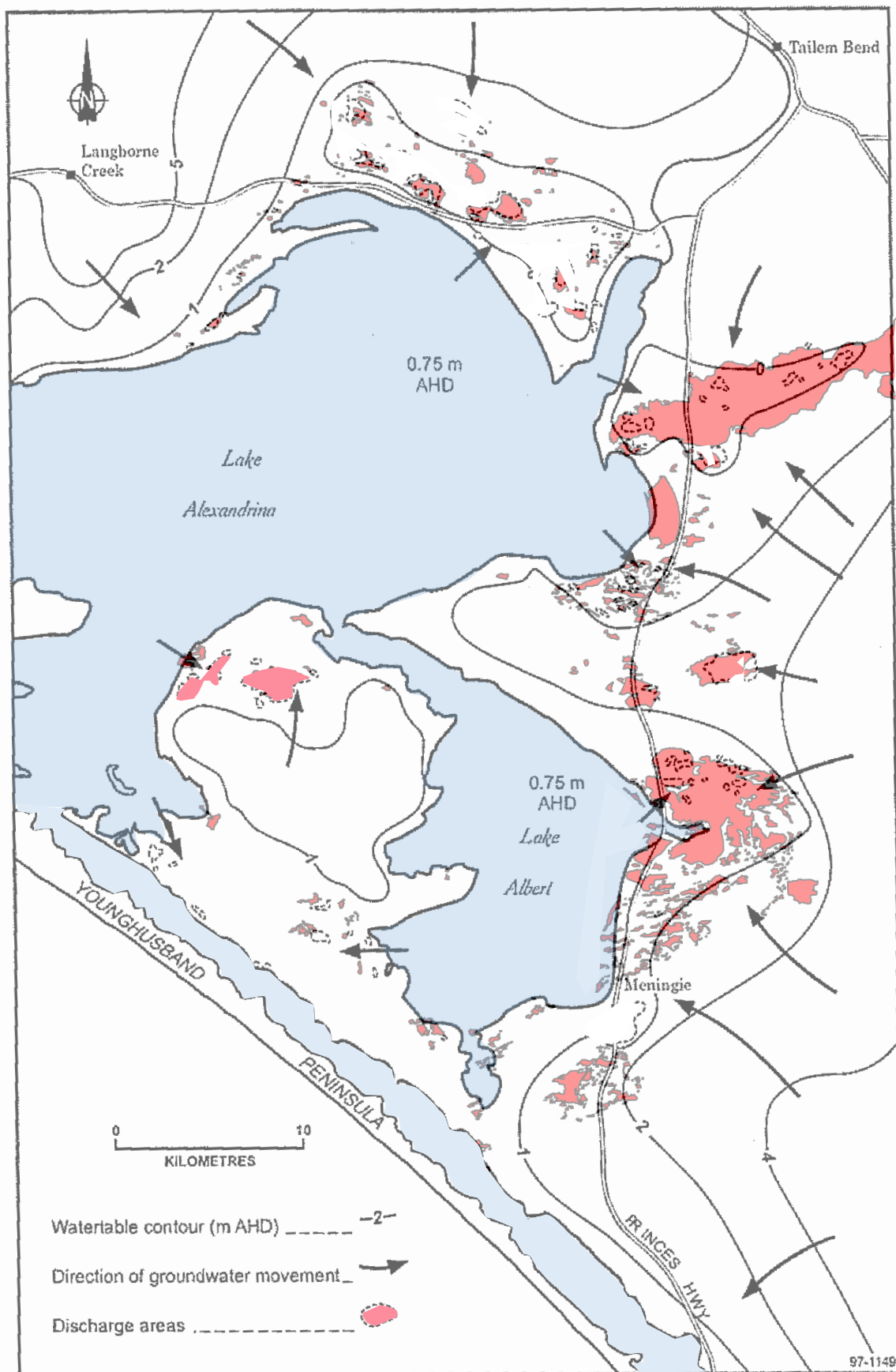


Figure 18. Areas of groundwater discharge adjacent to the lakes

11 Highlands

The SA Highlands form a continuous arc along the western margin of the Murray Basin from the Southern Ocean to the border with NSW. They occur in Neoproterozoic and Cambrian rocks which form the Mt Lofty Ranges to the south and the Olary Ranges in the north.

With the rain bearing weather systems approaching from the west, there is a strong rain shadow effect from west to east across the ranges into the plains of the Murray Basin (Fig. 2). There is also a general decrease in rainfall from south to the north. Because of the low rainfall, only several ephemeral streams emanate from the Ranges.

Immediately to the north of the Marne–Saunders PWRA in the Mt Lofty Ranges, the geology is dominated by the Cambrian Kanmantoo Group which consists of metamorphosed schists and sandstones. These rocks are generally tight and impermeable, and together with reduced recharge due to the rain shadow effect, result in low yields (< 3 L/sec), and groundwater salinities too high for irrigation development (2000 – 3000 mg/L). The land use is predominantly cereal cropping and grazing (Fig. 2).

Northwest of Morgan, Precambrian siltstones, sandstones and dolomites form parallel ridges separated by broad valleys containing silt, clay and sand alluvium. Sheep grazing predominates. Wells are mostly located in drainage lines yielding stock supplies only with salinities varying between 4000 – 8000 mg/L with several values over 10 000 mg/L.

Because of the current absence of groundwater development, no prescribed areas have been established and no estimates of sustainable yield have been determined. There is potential for future demand from mining developments, particularly for high grade iron ore in the Olary Ranges. There is virtually no monitoring due to the negligible extraction, however in the Burra area, monitoring suggests low recharge with a noticeable watertable response in very wet years.

Although stream salinities are moderate to high and limit biodiversity potential, permanent water and baseflow reaches provide a good physical habitat which have a high reliance on localised groundwater discharge from the fractured rock aquifers. The best examples are the permanent waterholes in the Burra Creek watercourse 20 km southeast of Burra.

12 Hydrogeology of the River Murray Alluvium

The previous sections have described the regional hydrogeology of the Murray Basin in South Australia which has confirmed the River Murray and its valley as the discharge area not only for the regional unconfined aquifers which are often saline, but also the underlying confined aquifers by upward leakage. It is not surprising that the salinity of the river increased significantly as it flowed downstream within South Australia before mitigation measures were introduced to control the impacts of land clearance and irrigation. Before the regional unconfined aquifers discharge to the river however, groundwater must flow beneath the floodplain within the alluvial sediments which encompass the river (except of course, where the river channel is adjacent to the side of the valley).

The river valley is highly variable, both in its shape and size and also its hydrologic regime. Figure 19 shows the wide variation in the shape of the river valley which reflects the interaction of several variables but mainly geology, which controls the bed morphology. However, the style of alluvial sedimentation within the valley is reasonably consistent. The geomorphology of the river valley has been discussed in detail by Thomson (1975).

The pre-European hydrologic regime would normally be variable because of changes in river discharge with time (usually of a seasonal nature) which would manifest as changes in river level. The watertable beneath the floodplain would therefore also fluctuate because of its connection with the river. However the construction of locks which were completed in 1939, has resulted in fixed river levels between the locks which show a stepped increase in level upstream. The floodplain watertable levels have now also stabilised as a result of the fixed river levels.

12.1 Geology of the alluvium

The River Murray in South Australia flows through sediments of the Murray Basin of Tertiary age which have been described earlier. Between Wellington and Overland Corner, the river flows in a narrow steep-sided gorge incised into the Murray Group Limestone. Upstream of Overland Corner, these limestones are downwarped across the Murrayville Monocline and the character of the river valley undergoes a dramatic change to a wide alluvial valley characterized by abandoned meander loops. Here, the river valley is contained within alluvial and lacustrine sediments of the Pliocene Sands.

Deposition of the alluvial sediments within the river valley can be assigned to two episodes related to post-glacial periods of rising sea levels (Rogers, 1988). These are the late Pleistocene 'upper terrace deposits' and the latest Pleistocene to Holocene Monoman Sands and Coonambidgal Formation. Both sequences consist of a fining upwards cycle.

The 'upper terrace deposits' are described in detail by Rogers (1988) at the Roonka Archaeological Site, 5 km north of Blanchetown. Deposition is thought to have commenced during a period of low sea level about 70 000 years ago and consist of a lower fluvial unit of medium grained sands (basal sands are coarser grained) overlain by silts and clays. This sequence can be correlated with the middle Pleistocene Rufus Formation of Gill (1973). Similar deposits are found in the Chowilla area (Firman, 1973).

After deposition of the 'upper terrace deposits', the river cut down through them during a period of low sea level. At the end of the last glacial period, a relatively rapid rise in sea level associated with the Flandrian transgression (between 17 000 and 7000 years BP) caused the Murray River to aggrade its valley with the coarse grained quartz sands of the Monoman Formation (Firman, 1973). The younger valley deposits of the Coonambidgal Formation are generally finer grained than the Monoman Formation and consist of alluvial clays, silts and sands. A carbon 14 date of 4040 ± 100 years Before Present was obtained from sub-fossil wood at the base of this unit at the Chowilla damsite (Firman, 1967). The Coonambidgal Formation extends to the present and includes modern point bars, lagoonal deposits and channel floor sediments.

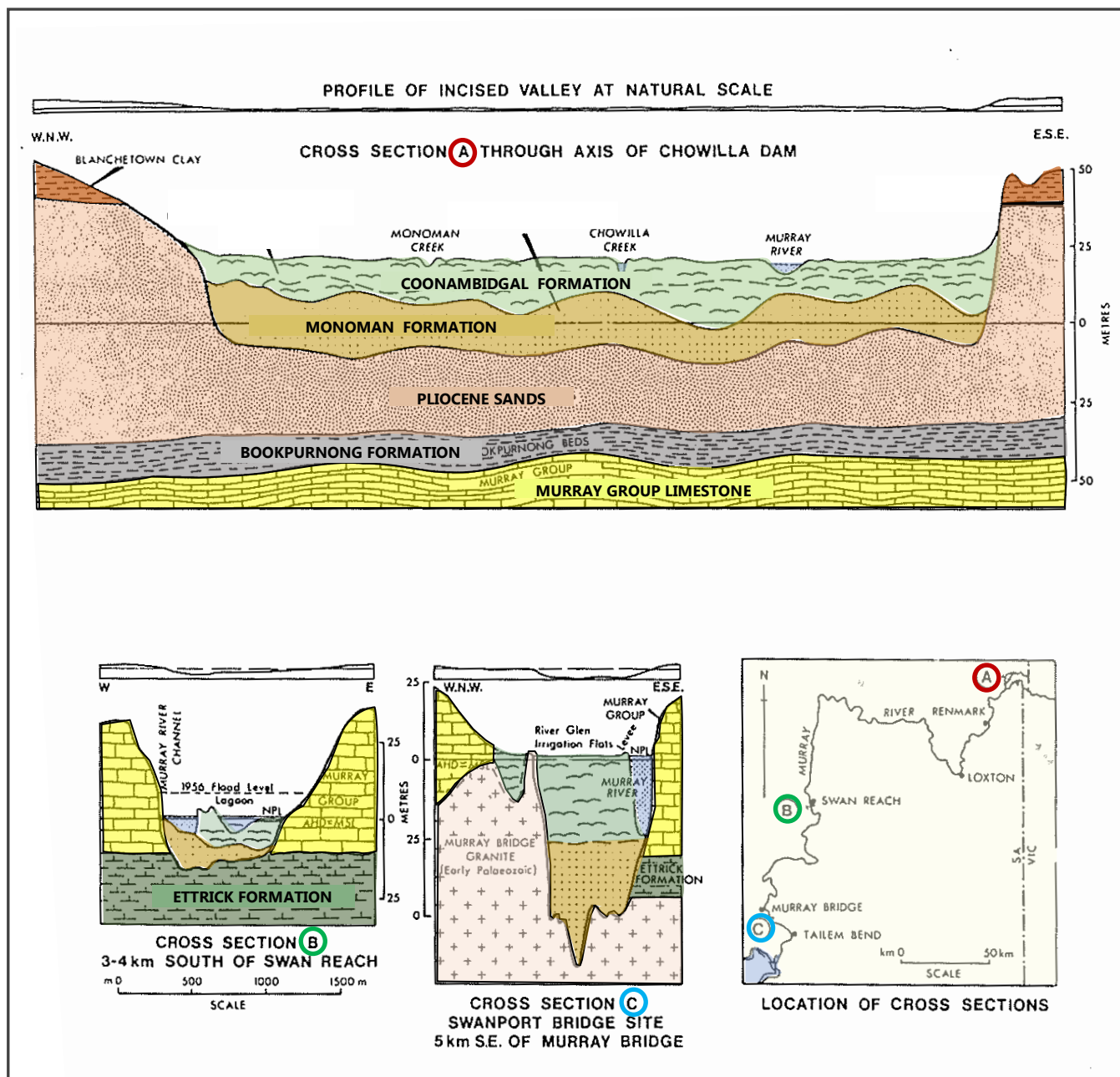


Figure 19. Various river valley cross sections (after Twidale, Lindsay and Bourne, 1978)

Groundwater processes beneath the floodplain of the River Murray play a crucial role in controlling regional groundwater discharge to the river. Under certain conditions, the floodplain itself is the zone of regional groundwater discharge by evapotranspiration with even the river contributing to the regional discharge by losing water to the alluvial sediments in some areas. The consequences of this process of evaporative discharge are the concentration of groundwater salinities to well over 35 000 mg/L and the salinization of low lying areas of the floodplain. The end result is the storage of large quantities of salt in the floodplain which may be mobilized to enter the river during or immediately after a flood event. For example, up to 1000 tonnes of salt per day has been recorded entering the River Murray from the Chowilla floodplain after a major flood.

Whether or not further anthropogenic changes to the hydrology of the floodplain will have a negative impact on river salinity is dependent on the type of groundwater discharge (either discharge to the river or evaporative discharge from the floodplain). Examples of further developments which may affect river salinity are the establishment of additional highland irrigation areas adjacent to the river valley with the potential for saline return flows, and the excavation of marinas in the floodplain which could enhance groundwater discharge to the river by exposing a greater surface water area to receive groundwater inflows. An understanding of the controls of the type of groundwater discharge will allow predictions to be made of the likely impacts of future developments on river salinity.

13 SA Murray Water Resource Plan

The discussion of the hydrogeology earlier in this report provides assistance for the development of the SA Murray Region WRP by informing a risk assessment of the capacity of the groundwater resource to meet the following requirements;

- meet environmental watering requirements
- groundwater and surface water connections
- maintain the productive base of groundwater
- assess salinity impacts, and
- prevent groundwater quality degradation.

Each one of these requirements will be discussed in turn.

13.1 Meet environmental watering requirements

The existence of terrestrial groundwater dependent ecosystems (GDEs) is largely determined by two factors; the depth to the groundwater below the ground surface and the salinity of the groundwater. Other aquatic GDEs reliant on groundwater discharge (baseflow) will be considered in the next section on the connectivity between surface water and groundwater.

As the depth to groundwater increases, the reliance on groundwater by vegetation decreases and alternative sources of water are required. Eamus et al (2006) suggest reduced reliance on groundwater where watertable depths exceed 10 m, negligible use in terms of total plant water use from depths of 10-20 m, and a low probability of groundwater use below 20 m.

High-salinity or brackish groundwater may reduce the likelihood of ecosystems using groundwater, although salt tolerance varies between different species. Bell (1999) reports that groundwater salinities of over 3500 mg/L are likely to affect salt-intolerant plants adversely, moderately-tolerant plants may tolerate salinities up to 7000 mg/L, and salt-tolerant plants may tolerate salinities up to 10 500 mg/L. However, River Red Gums are known to tolerate salinities up to around 18 000 mg/L.

Areas of good quality groundwater where extractions are currently occurring are covered by Water Allocation Plans (WAPs) which are required to assess the needs of water dependent ecosystems. Investigations for the Mallee WAP found no stygofauna or aquifer dependent ecosystems, mainly due to the large depth to the watertable. The Peake-Roby-Sherlock WAP describes only saline wetlands on the low-lying Coastal Plain that are connected to the shallow saline Quaternary Limestone aquifer (which is not currently used for extraction).

Figure 20 presents the depth to the watertable throughout the SA Murray WRP area. It is greater than 30 m over the vast majority of the area, within which it can be reasonably assumed that there are no GDEs dependent on groundwater. For the sedimentary aquifers, the exceptions are the River Murray floodplain (and adjacent areas of highland irrigation), the saline groundwater discharge areas around Noora to the east of Loxton and the low-lying Coastal Plain to the southwest. In the highlands to the north and west, there is little information but at the lowest points in the broad valleys, depths to the watertable of about 5 m would be expected.

The watertable salinity is shown in Figure 21. It can be seen that groundwater salinities are over 7000 mg/L over most of the SA Murray WRP area and in particular, beneath the low-lying Coastal Plain and adjacent to the River Murray floodplain. Therefore in the areas where shallow groundwater could potentially support GDEs, the salinities are too high and actually present a threat to ecosystems on the Coastal Plain through dryland salinization.

The likelihood of future development of the mostly saline groundwater within the SA Murray WRP area is quite low, but if it did occur in the sedimentary aquifers, it is likely to have a beneficial effect on the environment rather than a deleterious one. There is a low risk that future development in the highland aquifers would affect known GDEs because they occur in rugged terrain in the Burra area.

13.2 Groundwater and surface water connections

13.2.1 Groundwater

All the major aquifer systems in the Murray Basin extend beneath State borders. South of the River Murray, the groundwater resources 20 km either side of the SA/Victorian border have been cooperatively managed since 1986 under the *Groundwater (Border Agreement) Act 1985*. The Border Groundwaters Agreement Review Committee is the body responsible for the joint management, which involves setting extraction limits and permissible rates of groundwater level lowering. The Agreement also specifies that five yearly management reviews be carried out.

North of the River Murray, the aquifers straddling the SA/NSW border contain brackish to saline groundwater. There is virtually no current use because of the poor quality and limited land capability. Future extractions for mining would only impact interstate resources if they occurred within several kilometres of the border and even then, the consequences would be negligible because of the lack of use of the resource which is mostly saline.

The only areas of good quality groundwater within the SA Murray WRP area are covered by Water Allocation Plans which require the impact of extractions on adjacent water resources to be considered, which includes leakage from overlying aquifers which is discussed later in Section 11.4.

13.2.2 Surface Water

The River Murray, Lower Lakes and the Coorong are the focus of discharge from all the regional sedimentary aquifers in the South Australian Murray Basin. As discussed previously, the groundwater salinities are mostly greater than 7000 mg/L where these discharges occur. In the early 1990s between the State border and Morgan, just over 1000 tonnes of salt entered the river each day (Smith and Watkins, 1993). Since then, the extensive development of salt interception schemes along the River Murray has significantly reduced salt loads to the River Murray salinity caused by the discharge of saline groundwater. Extraction of approximately 10 000 ML/yr of saline groundwater has prevented about 500 tonnes/day of salt from entering the river.

Low lying saline areas on the river floodplain and surrounding the Lower Lakes and the Coorong intercept (by evaporative discharge) some groundwater flow that would have otherwise discharged to surface water features.

Within the SA Murray WRP area, streamflow in the highlands is highly ephemeral with creeks usually flowing only in very wet years. Any future groundwater extractions will have negligible impact on these intermittent flows. However isolated permanent water and baseflow reaches provide a good physical habitat for aquatic GDEs which have a high reliance on localised groundwater discharge from the fractured rock aquifers. The best examples are the permanent waterholes in the Burra Creek watercourse 20 km southeast of Burra.

13.3 Productive base of groundwater

As stated previously, areas of low salinity groundwater where extractions are currently occurring are covered by the Mallee and Peake-Roby-Sherlock WAPs. Determination of the sustainable limits for extraction in these Plans has used numerical groundwater flow modelling to take into account considerations such as structural integrity (by ensuring pressure levels of confined aquifers do not fall below the confining layer) and the consequences of inter-aquifer leakage (Barnett and Osei-Bonsu, 2006 and Barnett and Yan, 2008). In any case, the risks to the structural integrity of aquifers or aquitards are low because of the presence of consolidated Tertiary limestones and the absence of large thicknesses of unconsolidated silts and clays that typically contribute to subsidence and other structural issues.

Because of the generally high salinities in all aquifers outside the PWAs, the most likely future demand is from mining developments, in particular heavy mineral sands. Such developments require a program for environment protection and rehabilitation (PEPR) under the Mining Act. DEWNR has significant input into formulating conditions on any groundwater extractions such as metering and monitoring, even though the groundwater resource may not be prescribed.

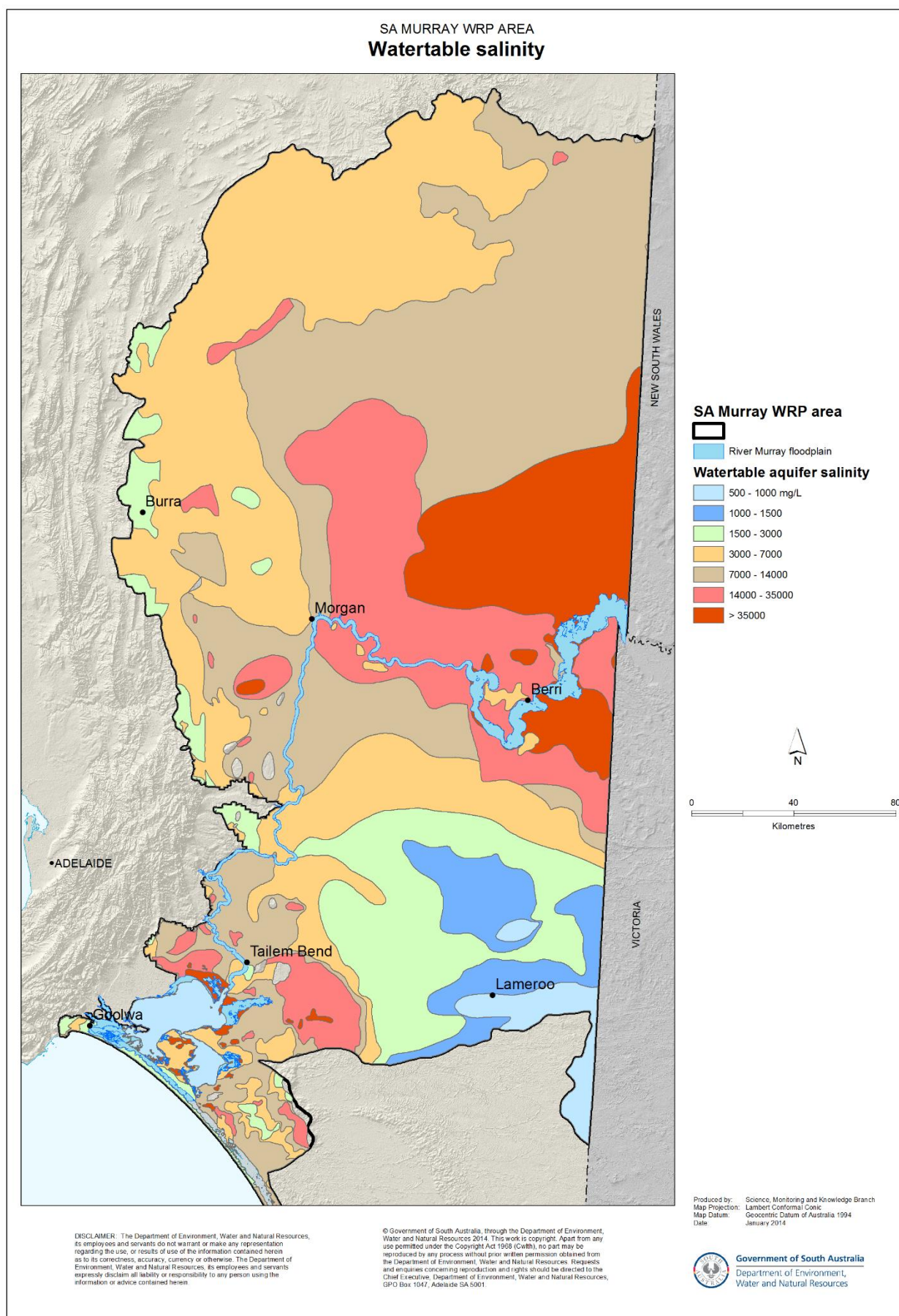


Figure 21. Watertable aquifer salinity in the SA Murray WRP area

13.4 Environmental outcomes relating to groundwater

In determining the sustainable limits for both the Mallee and Peake-Roby-Sherlock WAPs, groundwater salinity impacts from extractions were considered. As the developed aquifers are mostly confined, other water quality degradation issues were not considered. Regular salinity monitoring is carried out and resource condition limits for both water levels and salinity have been established.

A groundwater salinity risk assessment was carried out for the Mallee PWA (Barnett, 2007) which found that all risks (due to inter-aquifer leakage and lateral inflows) are long term over time frames of decades to hundreds of years. Numerical groundwater flow modelling (Barnett and Osei-Bonsu, 2006) found that in the area of maximum drawdown (and greatest potential for downward leakage), small increases of 40 mg/L (which is 4 % of the current salinity level) were predicted after 25 years. This increase is smaller than the variation in observed values.

In the Peake-Roby-Sherlock PWA, the groundwater salinity impacts from extractions from the Renmark Group confined aquifer were determined by groundwater flow modelling (Barnett and Yan, 2008) that predicted drawdowns due to extractions over 5000 ML/y will cause inflows of saline groundwater from the west, resulting in the stock salinity limit being exceeded within 200 years, as well as creating a high risk of collapse of the confining layer and depressurization of the confined aquifer. However if extractions remain below 1800 ML/yr, the stock limit will not be exceeded within 200 years.

Outside the PWAs, the high groundwater salinities mean there is a low likelihood of future development and even if this did occur, the consequences of any resultant changes in salinity would be minimal and highly unlikely to lead to a change in the beneficial use.

14 Groundwater monitoring

There are a number of networks monitoring the groundwater resources in the SAMDB NRM Region. Apart from the monitoring of resource condition in the PWAs discussed earlier, there are several networks in the non-prescribed areas that monitor the impacts of a number of different processes including ;

- drainage beneath irrigated areas adjacent to the River Murray
- increased recharge following the clearance of native vegetation
- the groundwater level decline due to extractions from salt interception schemes (SIS), and
- the groundwater response to the pumping of SIS water into disposal basins.

Due to the high groundwater salinities within the non-prescribed areas, there is no significant irrigation. Consequently, monitoring the impacts of irrigation extractions only occurs in the prescribed areas i.e. extraction from the Murray Group Limestone aquifer in the Mallee and Marne Saunders PWAs, and the confined Renmark Group aquifer in the Peake-Roby-Sherlock PWA. Groundwater status reports are produced on an annual basis for these PWAs and can be accessed at ; <http://www.waterconnect.sa.gov.au/Systems/GSR>

Figure 23 shows the location of monitoring wells in the SAMDB NRM Region. The water level data from these wells can be found on <http://www.waterconnect.sa.gov.au/Systems/GD>. Because of the generally high groundwater salinities, salinity monitoring is not a high priority in the non-prescribed areas. An assessment of the groundwater level trends throughout the region was carried out by Barnett (2008), and an updated summary is presented below for each of the regions used earlier in this report to describe the hydrogeology.

14.1 Riverland

Drainage beneath highland irrigation areas has formed watertable mounds which have displaced saline groundwater to the River Murray and floodplain. In recent years, the levels of the mounds have stabilised and are beginning to decline as a result of salt interception scheme pumping, rehabilitation of the delivery systems and improved irrigation practices. This declining trend was exacerbated by reduced irrigation applications during to the drought. Figure 22 presents representative trends from some of the irrigation areas.

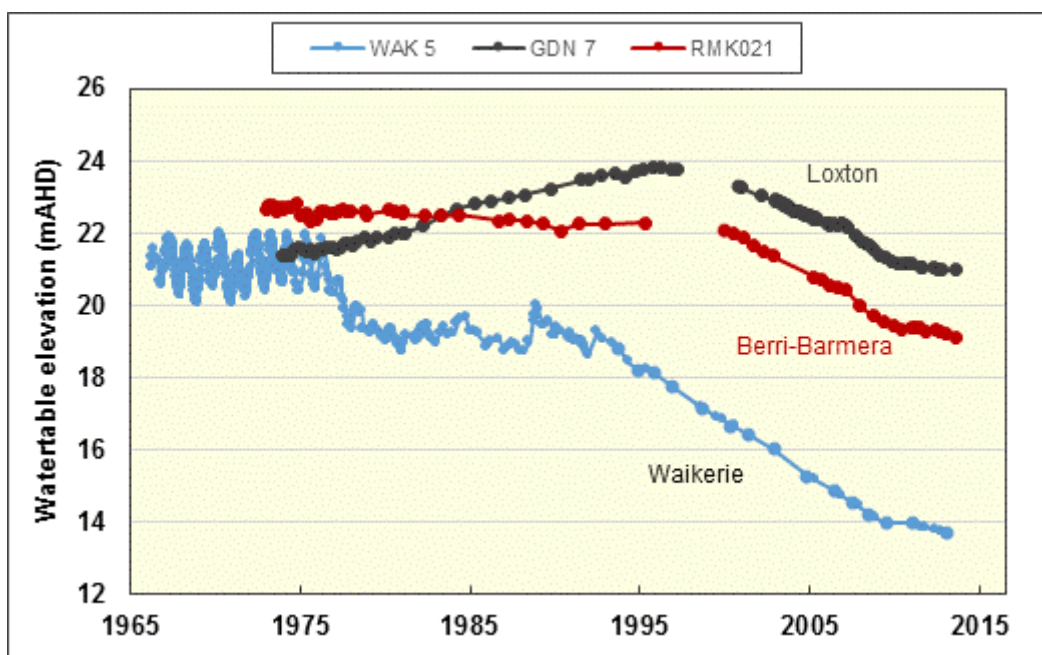


Figure 22. Representative hydrographs from irrigation areas in the Riverland

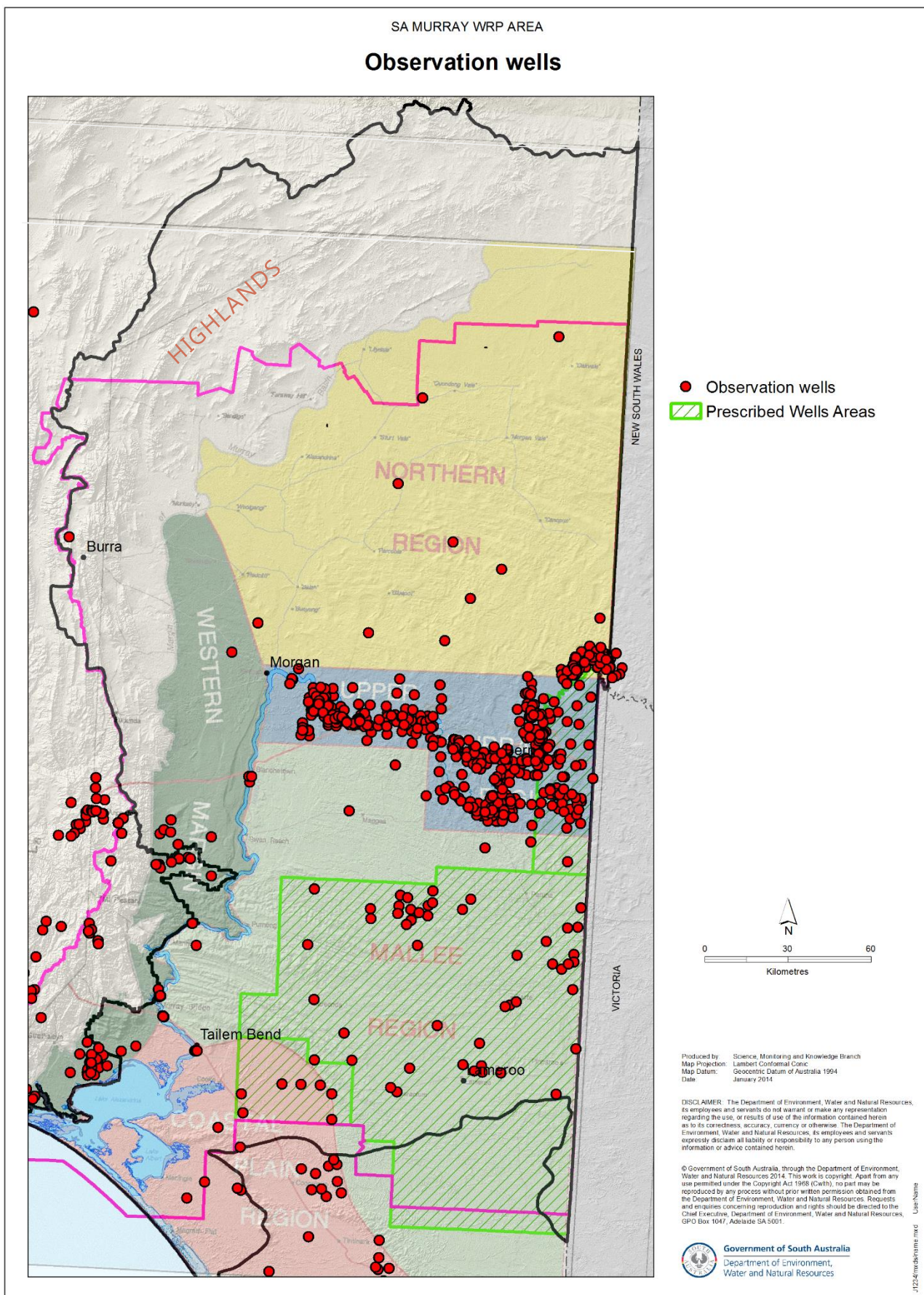


Figure 23. Location of observation wells

Some monitoring networks assist with the operation of the SIS schemes which are designed to lower groundwater levels to (or just below) river pool levels, while others monitor the impacts of pumping the SIS water into disposal basins. Figure 24 presents the trends from the Noora Disposal Basin located to the east of Loxton, and the Stockyard Plains Disposal Basin located to the southwest of Waikerie.

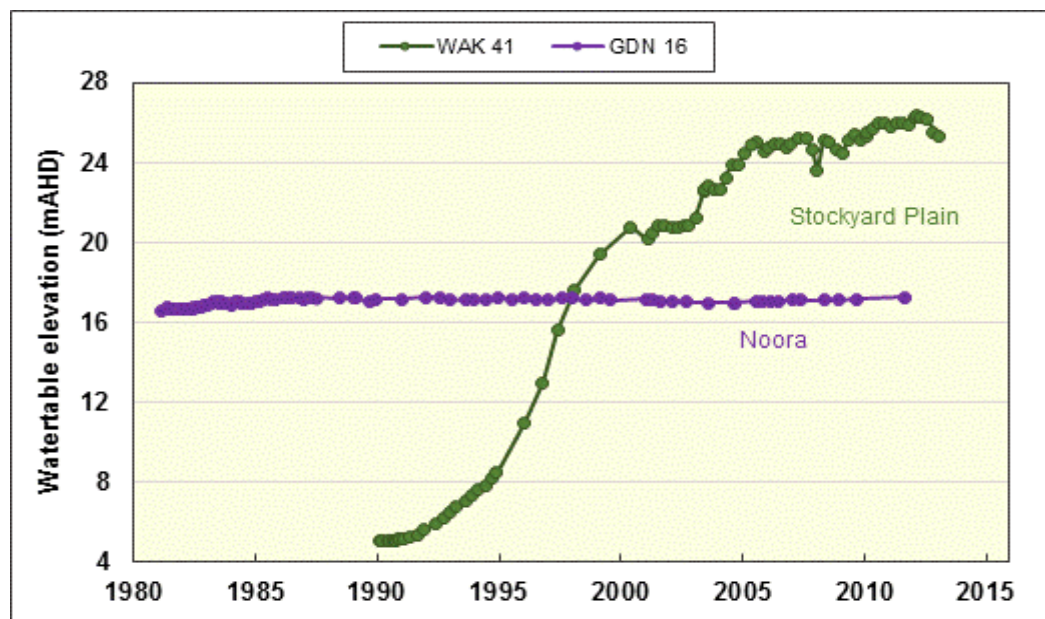


Figure 24. Representative hydrographs from disposal basins in the Riverland

14.2 Coastal Plain

Groundwater salinities in this region are too high for irrigation, but monitoring has been carried out since 1987 to observe rising watertables and dryland salinity risk resulting from land clearance. The response to clearing varies according to the depth to the watertable. In areas where the watertable is deeper than 10 m, the response is gradual and delayed as shown by observation well CLN 1 in Figure 25. In areas of shallower watertables, the water levels have a greater and more immediate response to rainfall patterns as shown by well JEF 2.

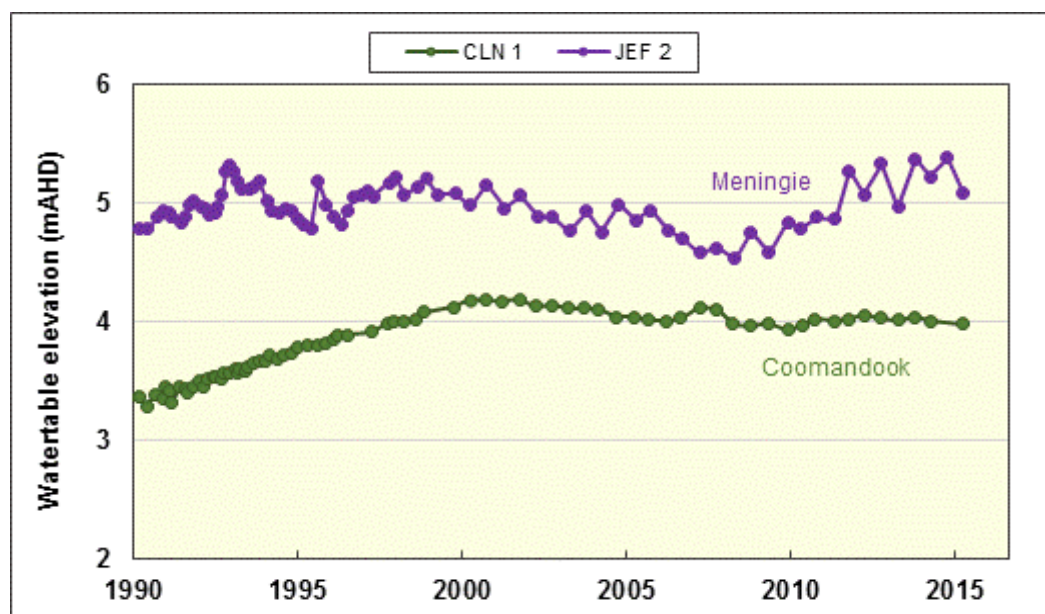


Figure 25. Representative hydrographs from the Coastal Plain

14.3 Western Margin

Monitoring in this region is concentrated in the Angas Bremer PWA and Marne- Saunders PWRA where groundwater extractions occur. Both water levels and salinities are monitored. Outside these prescribed areas, high salinities result in no significant groundwater extraction apart from occasional stock water use. Consequently there are no other monitoring networks.

14.4 Highlands

Because of the generally high groundwater salinities and low yields from the fractured rock aquifers outside the prescribed areas, there is no significant groundwater extraction apart from occasional stock water use. Consequently there are no monitoring networks established in this area.

14.5 Northern Region

The network in this region is monitored very intermittently as trends are quite stable as there is virtually no extraction because of the high salinities and no widespread clearance that could have increased recharge rates. The remoteness and access issues also contribute to the infrequent monitoring.

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APPENDIX A – GEOLOGY

BASEMENT

For the purposes of this report, basement includes any pre-Cainozoic sediments. Consequently, basement lithologies vary from Permian clays to Neoproterozoic metasediments. Commencing with the oldest, the basement units are discussed below, and summarized in Table A1. A Pre-Cainozoic basement rock-relationship diagram is shown as a northeast to southwest cross section in Figure A1.

Table A1. Pre-Cainozoic basement geology

Age	Geological Units	Lithology	Occurrence
Neo-Proterozoic (Adelaidean)	Various	Siltstones, sandstones, shales	Adelaide Fold Belt (Mt Lofty and Olary Ranges)
Cambrian	Kanmantoo Group	Phyllites, slates, gneiss	Adelaide Geosyncline (Mt Lofty Ranges)
Ordovician	Various	Granite	Padthaway Ridge
Devonian	? Grampians Group	Quartz sandstone	Nadda Basin
Permian	Cape Jervis Formation	Diamictites, clay and minor sand	Troubridge Basin
Cretaceous	Monash Formation	Siltstone and shale	Renmark Trough

The Neoproterozoic metasediments of Adelaidean age from the Adelaide Geosyncline comprise siltstones, sandstones and shales with minor carbonate and tillites. As well as forming the Mount Lofty and Olary Ranges, they have been encountered beneath the northwest margin in stratigraphic, mineral and groundwater investigation drillholes (Rogers, 1978).

Metamorphosed rocks of the Cambrian Kanmantoo Group (phyllites, slates and gneiss) occur on the eastern side of the Mount Lofty Ranges and their equivalents have been intersected in drillholes over most of the Murray Basin in South Australia (Rankin et al, 1992). The Delamerian Orogeny which metamorphosed the Kanmantoo Group, ended in the Early Ordovician with the widespread intrusion of granitic and mafic bodies which form the Padthaway Ridge, a NW-SE trending basement high near the southwest margin of the basin.

The Nadda Basin to the north of the River Murray contains Permian and possibly Devonian grey quartz sandstones which immediately underlie the Cainozoic sediments. The Devonian sediments are probably non-marine and may correlate with the ?Upper Silurian - Lower Devonian Grampians Group (Brown and Stephenson, 1991) which consists of quartz sandstone, red siltstone and mudstone and form in outcrop, the well known ranges of the same name south of the Murray Basin in Victoria.

The Lower Permian glacio-marine sediments of the Cape Jervis Formation comprise diamictites, clays and minor interbedded sand which underlie Tertiary sediments in the southwest portion of the basin beneath the Coastal Plain in the vicinity of Lake Alexandrina and Coonalpyn.

Tertiary sediments directly overlie a lower Cretaceous sequence in the Renmark Trough area. The uppermost Cretaceous unit, the Coombool Member, is fluvio-lacustrine in origin and consists of greenish-grey, chloritic siltstone, sandstone and shale. The Renmark Trough also contains possible Upper Silurian - Lower Devonian sediments up to 3000 m thick (Thornton, 1974).

Figure A2 depicts structure contours of the surface of the basement. Apart from the complex block-faulting at the Morgan and Hamley Faults, the basement deepens gradually from the margins to a maximum depth of about 550 m in the Renmark Trough.

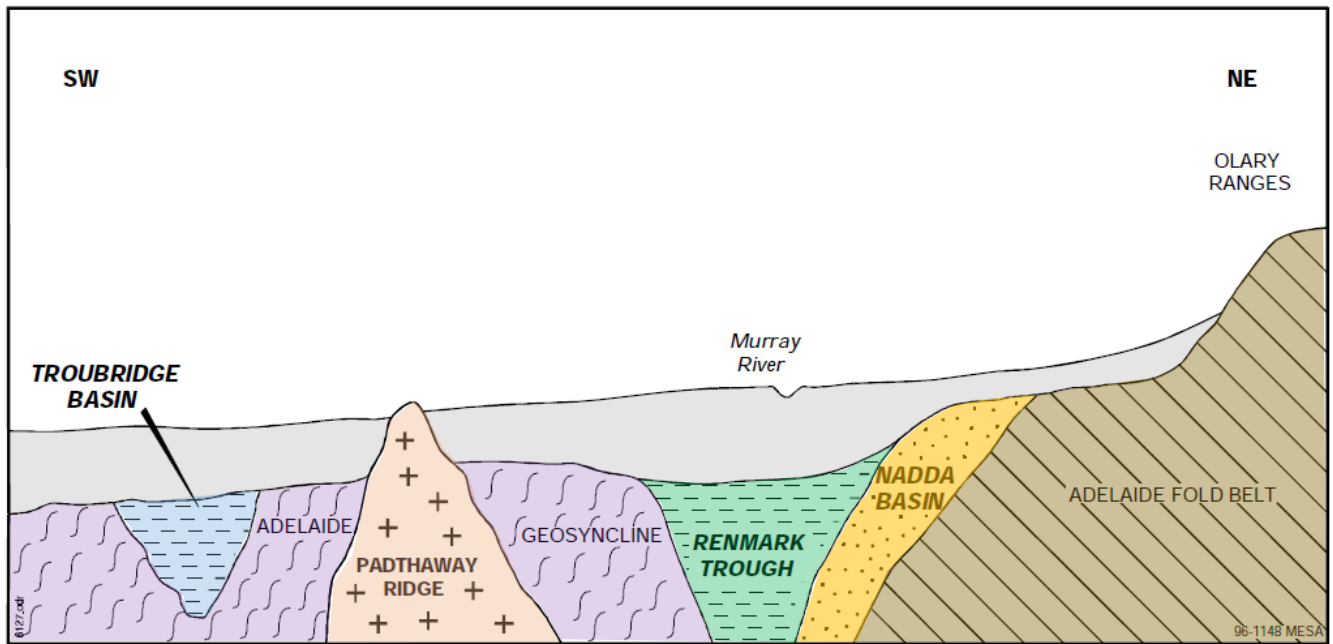


Figure A1. Pre-Cainozoic basement rock relationship diagram

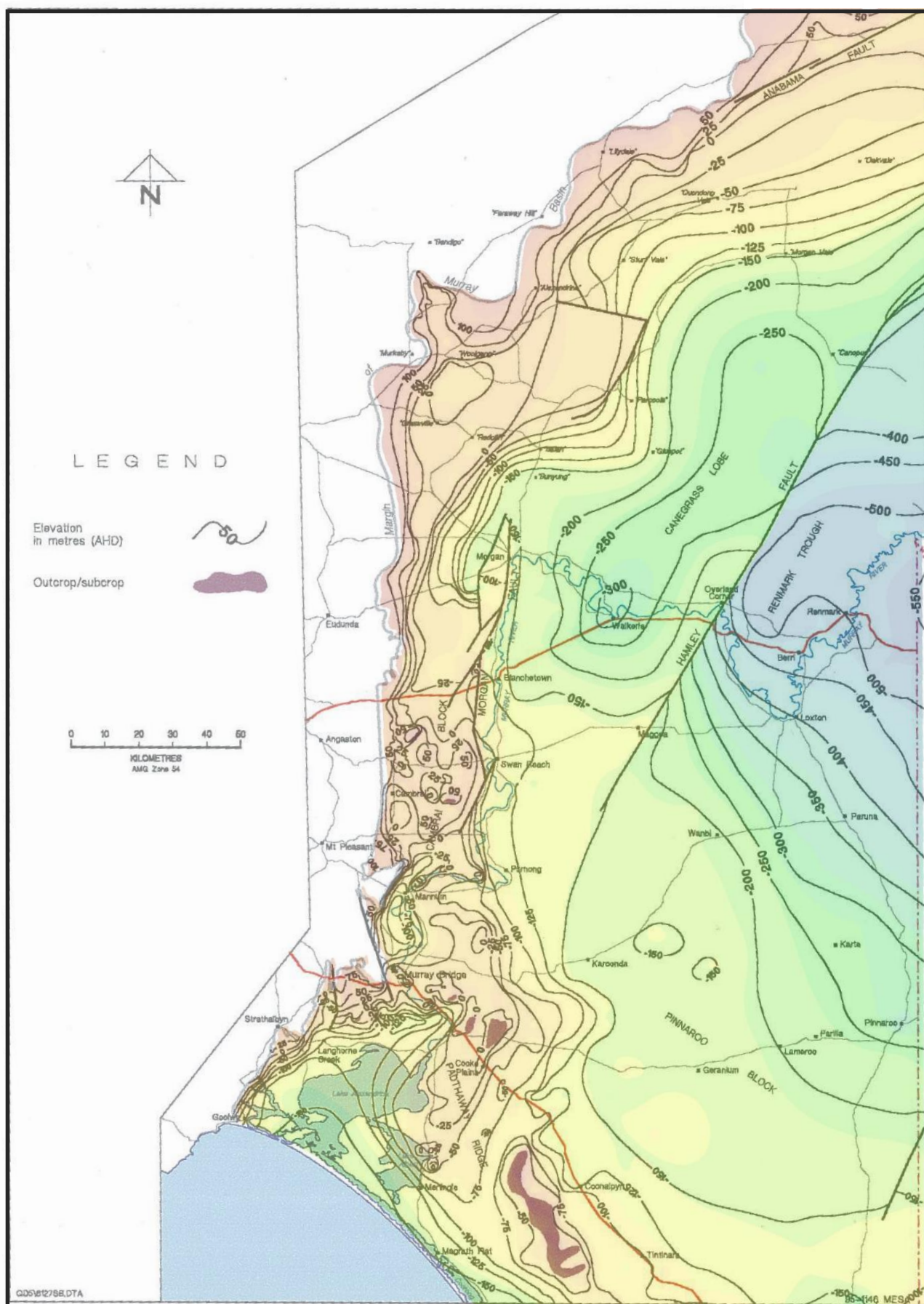


Figure A2. Pre-Cainozoic basement elevation contours (after Barnett, 1989)

TERTIARY

The Tertiary geology of the Murray Basin will be described on the basis of the three major depositional sequences which were shown previously in Figure 2 and summarised in Table A2. Palaeofacies diagrams courtesy of Australian Geological Survey Organisation (AGSO) are also presented for each of the sequences.

Palaeocene - Eocene Depositional Sequence

The base of the Tertiary sequence consists of a considerable thickness of fluvial, medium to coarse quartz sands with minor interbedded carbonaceous clasts called the Warina Sand. Limited palynological evidence suggests a Palaeocene - Middle Eocene age for this unit which is intersected only in the deeper parts of the basin i.e. the Renmark Trough. It is overlain by interbedded sands, silts, carbonaceous clays and lignites of the Olney Formation of Middle Eocene to Early Oligocene age which were widely deposited in fluvio-lacustrine, deltaic and extensive swamp environments (Brown and Stephenson, 1991) (Fig.A3). Together, these two units constitute the Renmark Group and attain a maximum thickness of 330 m near Renmark.

The Olney Formation is more widespread than the Warina Sand and contains a limited marine influence based on micropalaeontological evidence near the top of the unit in the western part of the basin (Ludbrook, 1961). Also in the upper part of the Olney Formation are sub-economic lignitic coal seams of the Moorlands Lignite Member (Harris, 1966). These were deposited in swamps formed in local depressions in basement around the western margin of the basin and have been subject to exploration at Moorlands, Peake, Sedan, Anna, Bower and near 'Pine Valley' to the north. There could be renewed interest in these deposits for unconventional gas exploration.

The Renmark Group intercalates with the Late Eocene Buccleuch Formation in the southwest corner of the basin (Fig.A3). Ludbrook (1961) described the standard sub-surface section in the Coonalpyn town bore and divided it into three informal units, each containing glauconitic marls, bryozoal limestones, carbonaceous clays and fossiliferous sands, respectively. These shallow marine sediments were originally considered entirely Eocene in age (Rogers, 1980). However, subsequent work has shown that these informal units are too inconsistent and sporadic to form a widespread subdivision. Ludbrook, together with Brown and Stephenson (1991), consider that deposition of the Buccleuch Formation was restricted to a palaeographic feature in the southwest of the basin called the Buccleuch Embayment (Fig. 6) which roughly coincides with the Coastal Plain region. Structure contours of the top of the Renmark Group are shown in Figure A4.

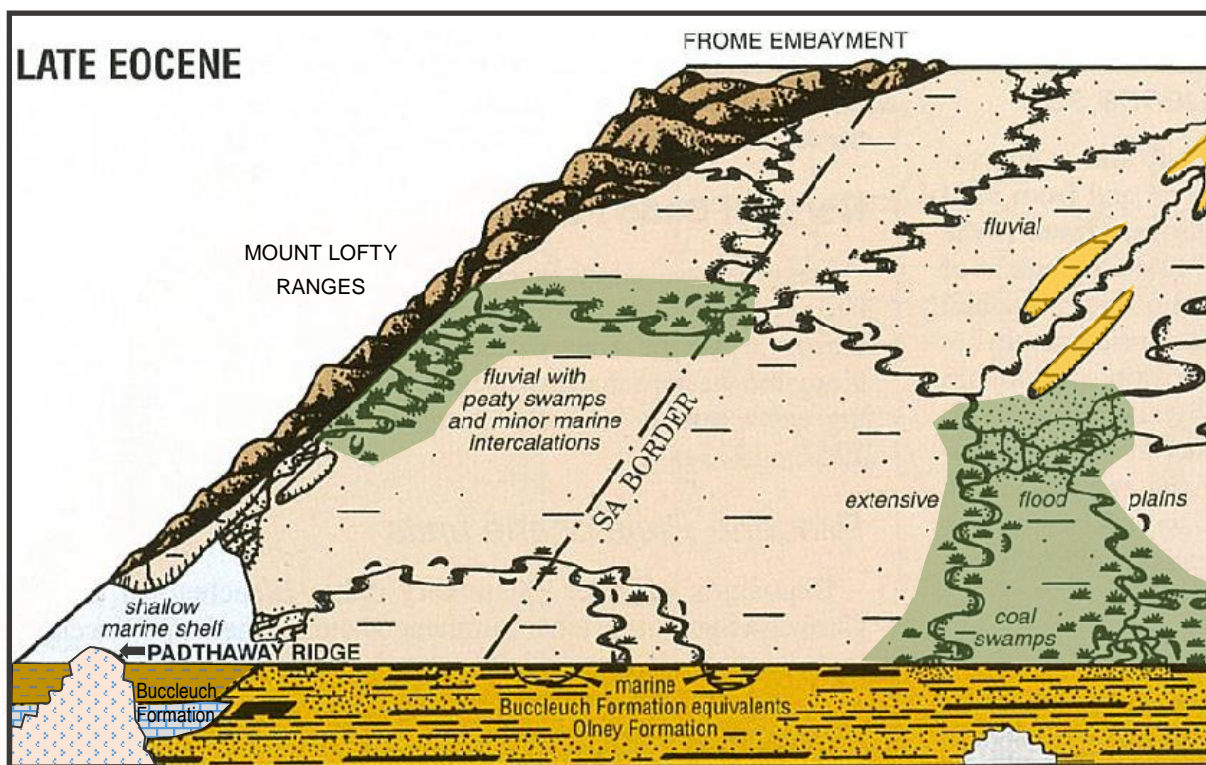


Figure A3. Late Eocene palaeofacies (courtesy AGSO)

Table A2. Tertiary stratigraphy

	AGE	UNIT	LITHOLOGY	MAXIMUM THICKNESS	ENVIRONMENT
UPPER MIOCENE - PLIOCENE SEQUENCE	LATE PLIOCENE	Norwest Bend Formation	Oyster beds and shelly sand	10 m	Estuarine
	PLIOCENE	Loxton - Parilla Sands	Unconsolidated fine to coarse sands and minor clay	50 m?	Fluvial and estuarine sand sheets with occasional stranded beach ridges
	LATE MIOCENE - PLIOCENE	Bookpurnong Formation	Glauconitic and shelly silt and clay	40 m?	Shallow marine
OLIGOCENE - MIDDLE MIOCENE SEQUENCE	LATE OLIGOCENE - MIDDLE MIOCENE	Olney Formation	Sand, clay and minor lignite	25 m	Fluvial and deltaic, prograding over marine sediments
		Geera Clay	Silty and occasionally lignitic clay	75 m	Tidal flat, marginal marine
		Winnambool Formation	Glauconitic and fossiliferous marl	100 m	Restricted marine, lagoonal
		Murray Group limestone	Fossiliferous limestone	140 m	Shallow marine
	OLIGOCENE - EARLY MIOCENE	Ettrick Formation	Glauconitic and fossiliferous marl	50 m	Restricted marine, lagoonal
	OLIGOCENE	Compton Conglomerate	Glauconitic and shelly sand	90 m	Transgressive shallow marine
PALAEOCENE - EOCENE SEQUENCE	LATE EOCENE - OLIGOCENE	Buccleuch Formation	Carbonaceous clay, bryozoal limestone, glauconitic marl and shelly sand	50 m	Restricted marine
	EOCENE	Olney Formation	Carbonaceous clay sand and silt	200 m	Fluvio - lacustrine, paralic
	PALAEOCENE - ? EARLY EOCENE	Warina Sand	Medium and coarse sand and minor silt	200 m	Fluvial

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Oligocene - Middle Miocene Depositional Sequence

A major relative rise in sea level in the Late-Oligocene resulted in great changes in sedimentation patterns in the western Murray Basin with the deposition of marine limestones and marls (Fig. A5).

The Compton Conglomerate represents the onset of this marine transgression and is described in type section by Ludbrook (1961) as containing "abundant rounded ironstone pebbles in a limonitic matrix." Lindsay and Williams (1977) described exposures of the Oligocene transgressive sequence along the southwestern margin of the Murray Basin and found Compton Conglomerate "or close equivalents" directly overlying basement and consisting of poorly fossiliferous sand to gravel, one to two metres thick. Drilling throughout the basin (Edwards 1982b, Barnett 1988a&b, 1992a) consistently intersected a grey-green, glauconitic and fossiliferous quartz sand, 10-15 m thick directly overlying pre-Tertiary basement or the Eocene Olney Formation. It is proposed that this unit be known as "Compton Conglomerate equivalents" as it fits into the classic marine onlap sequence as the basal clastic unit.

Above this basal unit, grey glauconitic marls of the Ettrick Formation (Ludbrook, 1961) were deposited as the Oligocene marine transgression covered a shallow marine platform which extended over most of the South Australian portion of the Murray Basin. As sea level rose, the marls were succeeded by shallow marine, Late Oligocene to Middle Miocene bryozoal calcarenites of the Murray Group. Although finer stratigraphic subdivisions of this group have been made - Mannum Formation, Morgan Limestone, Pata Limestone, Glensforlan Formation etc. (Lukasic and James, 1998), the overall similarities in lithology (especially in drillhole samples) and the unknown extent of the various units make the use of the term "Murray Group Limestone" more convenient on a regional basin scale.

Towards the northwest margin of the basin in South Australia, the shallow-marine platform was bounded by a narrow zone of restricted marine and lagoonal environments, which were in turn flanked by a marginal marine and tidal flat zone (Brown and Stephenson, 1991). Consequently, the fossiliferous limestones grade laterally into grey glauconitic marls of the Winnambool Formation deposited in the restricted marine environment. These then grade into extensive black carbonaceous clays of the tidal flat zone called the Geera Clay (Fig. A5). Figure A6 presents structure contours of the top of the Murray Group Limestone.

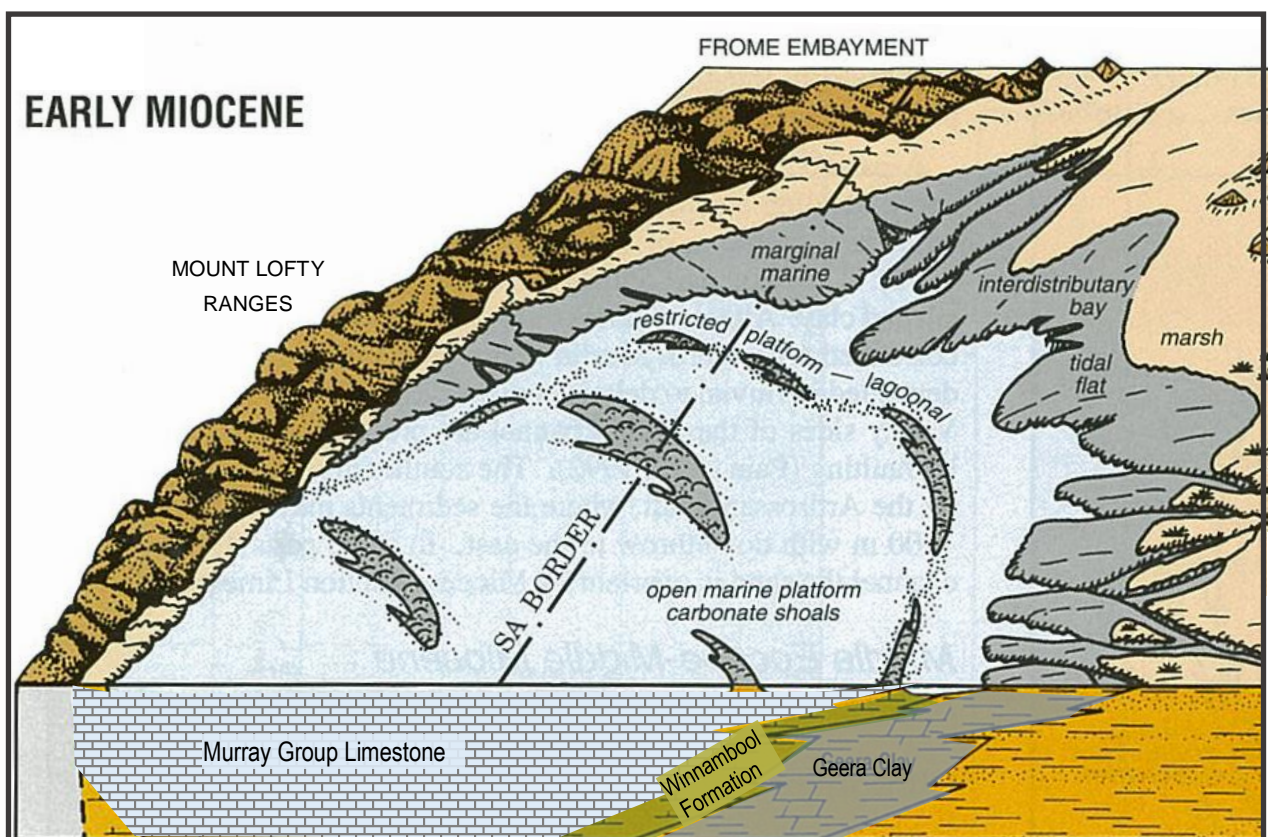


Figure A5. Early Miocene palaeofacies (courtesy AGSO)

A major regression occurred at the end of the Mid-Miocene. As the marine and marginal marine environments retreated seaward, so did the sediments associated with them. As a result, the Geera Clay and Winnambool Formation have partly prograded back over the top of the Murray Group limestone (Fig. 5). Even the non-marine lignitic sands and clays of the Olney Formation have prograded back over the Geera Clay in the far northeast corner of the basin in SA (Barnett, 1994b).

Upper Miocene - Pliocene Depositional Sequence

Deposition of the third major sedimentary sequence commenced in the late Miocene and continued through to the Late Pliocene (Drexel and Priess, 1995). The transgression deposited the shallow marine dark grey, glauconitic and shelly silts and clays of the Bookpurnong Formation in the eastern part of the basin in South Australia, and subsequently the marginal marine sands and clays of the basal Loxton Sands (Fig. A7). Structure contours are presented in Figure A8.

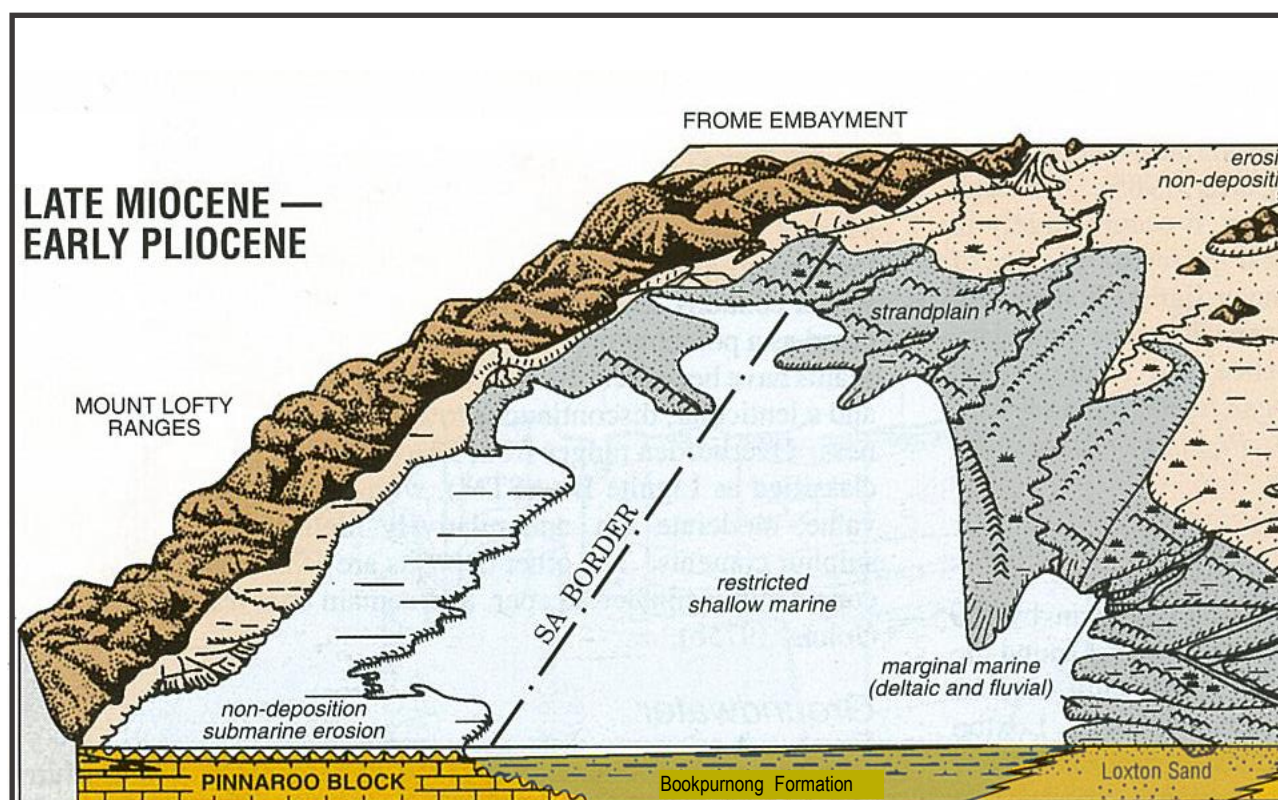
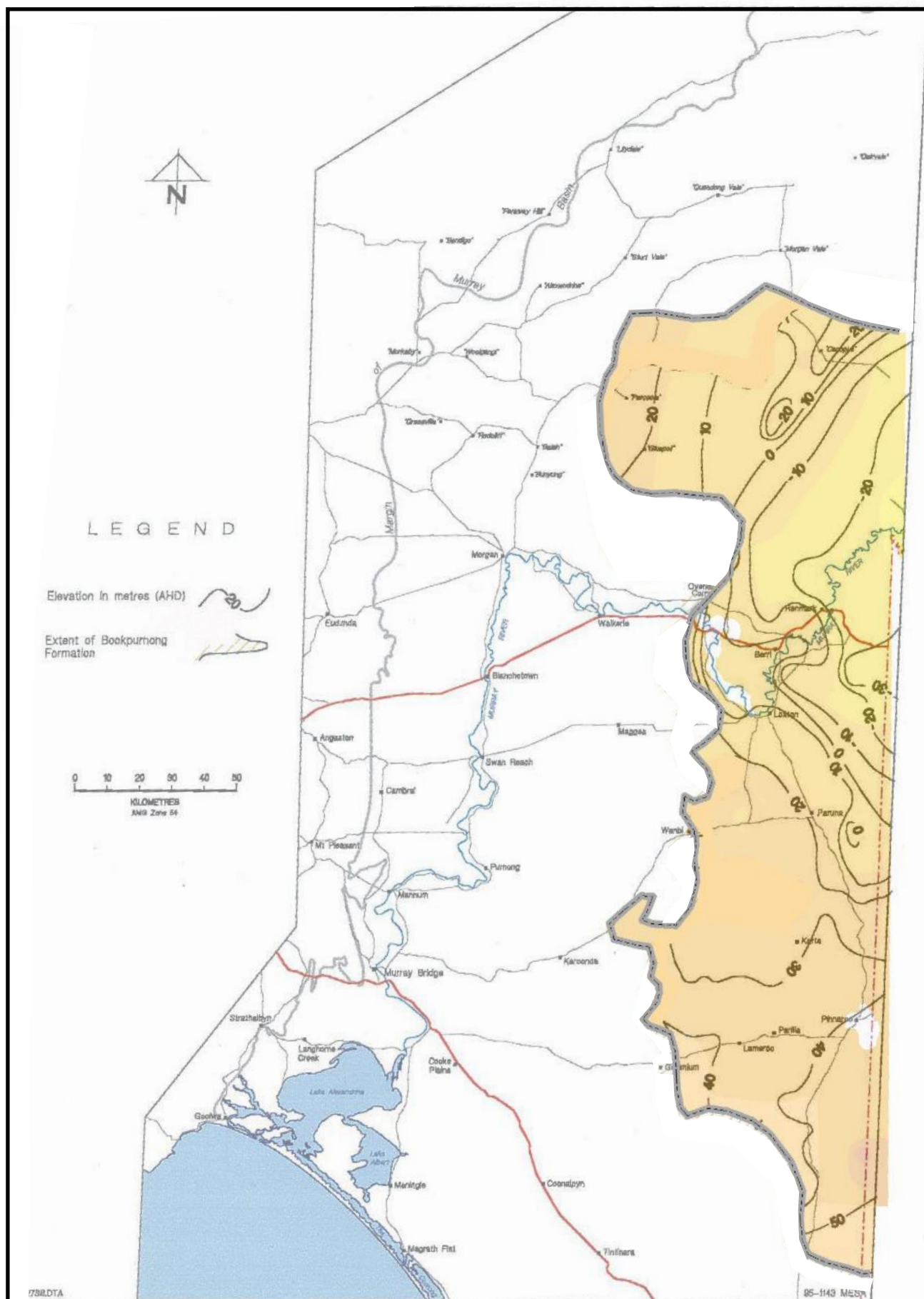


Figure A7. Late Miocene – Early Pliocene palaeofacies (courtesy AGSO)

The Early Pliocene Loxton Sand comprises glauconitic, micaceous and shelly fine sand, overlain by planar and cross-bedded fine to coarse-grained sand and fine gravel, with abundant shell debris. It is interpreted as an upward-coarsening regressive sequence of shallow water marine and marginal marine sediments passing up into beach and coastal barrier deposits. The Loxton Sand is overlain by the non-marine Parilla Sand, composed of unfossiliferous fine to medium-grained clayey quartz sand with thin beds of sandy clay. The formation was derived mainly from the Loxton Sand by aeolian and fluvial reworking (Drexel and Priess, 1995).

Because of similar lithologies and confusing definitions from different States, the whole sand sheet is referred to in this report as the "Loxton-Parilla Sands" (Fig. A9). They generally consist of yellow-brown fine to coarse sands which are sometimes dark grey and silty near the base.

A minor eustatic high stand of sea level in the Latest Miocene to Early Pliocene deposited oyster beds and calcareous sandstones of the Norwest Bend Formation (Ludbrook, 1961) in an ancestral estuary following the course of the lower River Murray, downstream of Overland Corner. Miranda et al (2008) have proposed a division into a lower sand-dominated member and an upper oyster coquina member and that tectonism in the western Murray Basin adjacent to the Adelaide Foldbelt has exerted a considerable control over the formation of these sediments.



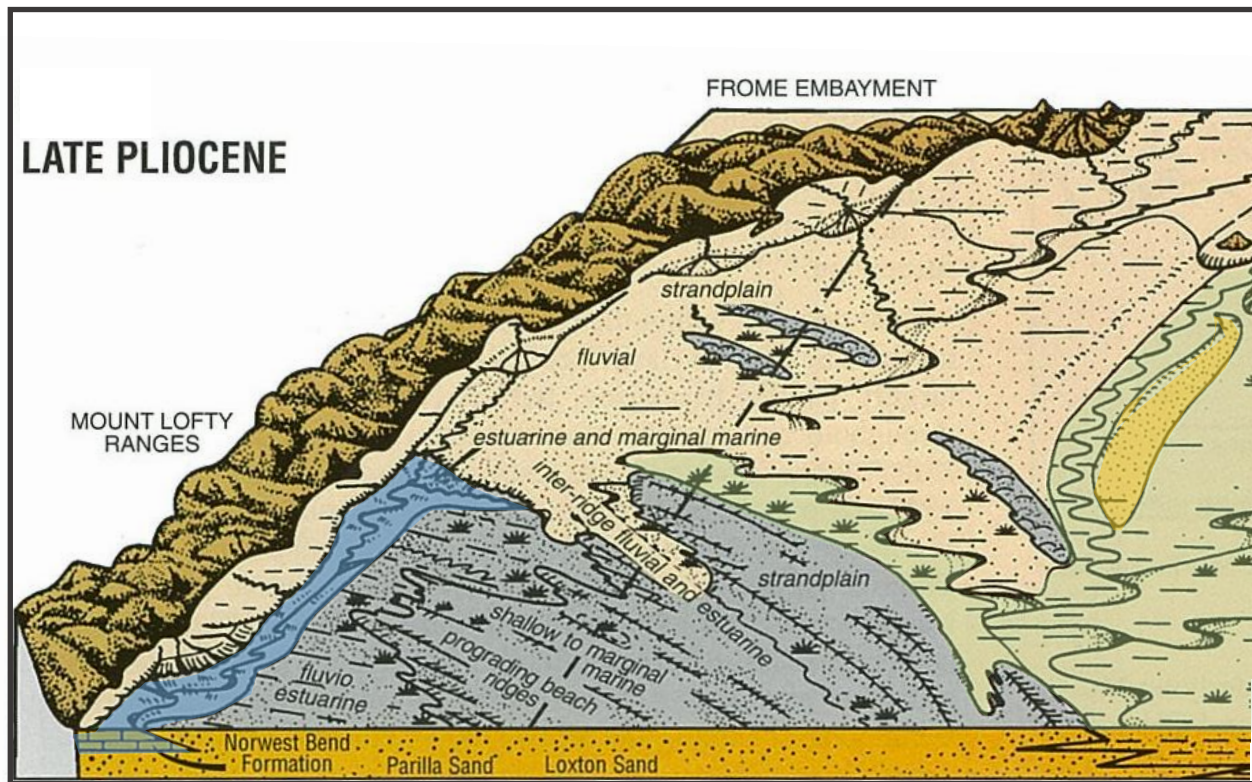


Figure A9. Late Pliocene palaeofacies (courtesy AGSO)

QUATERNARY

The Quaternary period is characterised by marked climatic oscillations and the development of many of the present-day geomorphological features. Uplift of the Pinnaroo Block about 2 million years BP led to tectonic damming of the palaeo-River Murray and the formation of Lake Bungunnia which covered about 30 000 km², and the deposition therein of the fluvio-lacustrine Blanchetown Clay in a cool, moist climate (Stephenson, 1986). The natural dam was breached about 700 000 years ago, and the lake rapidly drained.

About 800 000 years ago, a marine transgression extended from the southwest only partially inland (Fig. 10) eroding away the older Pliocene and Miocene sands and limestones and in their place, depositing shallow marine limestones of the Coomandook Formation (Rogers, 1980). This transgression led to the formation of the low-lying Coastal Plain. These Quaternary limestones contain reworked material from the older Miocene limestone and is therefore often difficult to distinguish them lithologically. As the sea retreated gradually in response to tectonic uplift, a series of stranded coastal ridges were formed comprising shelly and sandy limestones of the Bridgewater Formation.

The onset of arid conditions about 500 000 years ago is reflected by a change from fluvial to aeolian and saline gypseous sedimentation. In the northern part of the basin in SA, the east-west linear dunes of the red-brown Woorinen Formation were formed by strong westerly winds during this arid phase (Firman, 1967), while to the south in the Mallee Region, linear and parabolic dunes of pale yellow sand comprising the Molineaux Sand were deposited (Firman, 1973). In the low-lying Noora-Yamba area near Renmark, saline playas consisting of lacustrine gypsiferous clay and gypsum-quartz sand mixtures of the Yamba Formation reflect the strong influence of groundwater discharge.

Around the basin margins, coarse grained colluvial and alluvial deposits of the Pooraka Formation formed extensive coalesced fans and scree slopes. Within the River Murray valley, alluvial sands of the Monoman Formation together with overlying silts and clays of the Coonambridgal Formation were deposited (Firman, 1973).

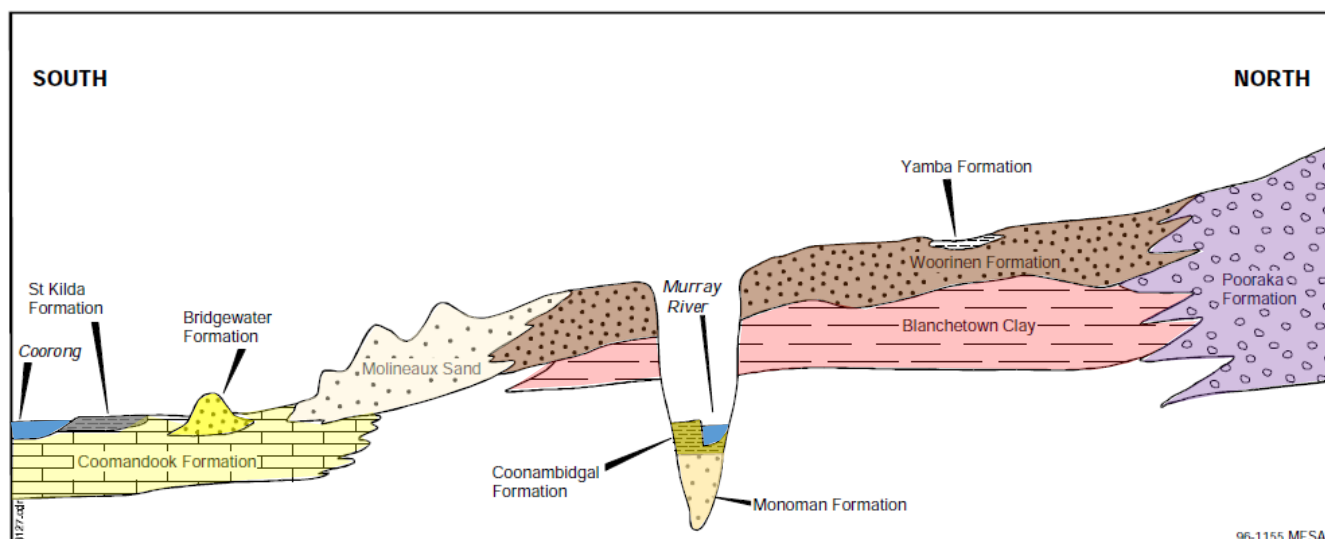


Figure A10. Quaternary sedimentary relationship diagram

About 6000 years ago, sea level rose to a point several metres higher than at present. This caused an expansion of the estuarine Lake Alexandrina and led to the deposition of the silt, sand and shell debris of the St Kilda Formation.

The Quaternary stratigraphy is summarized in Table 3. The extent of these units can be seen on published 1:250 000 scale geological maps. A sediment relationship diagram is shown in Figure A10, while a palaeofacies map is presented in Figure A11.

Table A3 - Quaternary stratigraphy

UNIT	LITHOLOGY	MAXIMUM THICKNESS	ENVIRONMENT
St Kilda Formation	Silt, sand and shell debris	3 m	Lacustrine and estuarine
Coonambidgal Formation	Silt and clay	25 m	Fluvial - Murray River valley
Monoman Formation	Sand and gravel	25 m	Fluvial - Murray River valley
Molineaux Sand	Unconsolidated sand	10 m	Aeolian - mobile dune fields
Yamba Formation	Gypsiferous clay	3 m	Evaporitic - groundwater discharge area
Woorinen Formation	Sand, silty clay	5 m	Aeolian - linear dune fields
Pooraka Formation	Clayey sand and gravel	30 m	Colluvial - alluvial fans and scree slopes
Bridgewater Formation	Sandy limestone	80 m	Aeolian - stranded beach ridges
Coomandook Formation	Fossiliferous sandy limestone	50 m	Shallow marine
Blanchetown Clay	Mottled clay	15 m	Freshwater lacustrine

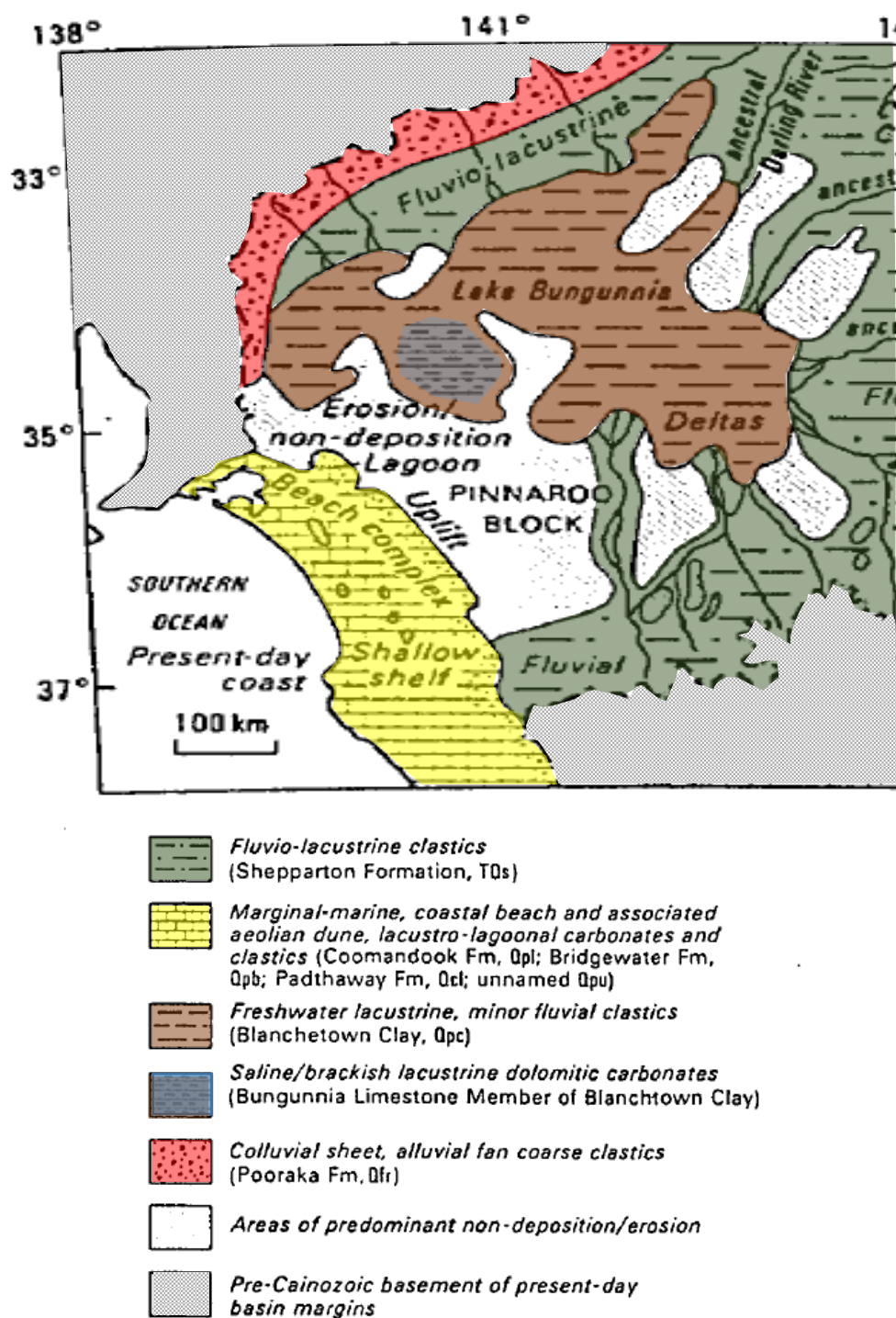


Figure A11. Quaternary palaeofacies (courtesy AGSO)

