Hydrogeological review of the Musgrave Province, South Australia

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CONTENTS

Figures

Tables

EXECUTIVE SUMMARY

The Musgrave Province is a crystalline basement that occupies an area of about 60,000 km^2 in the north western part of South Australia. The area is a part of the Anangu Pitjantjatjara Yankunytjatjara (APY) Lands and is home to several aboriginal communities. The Musgrave Province has a semi-arid climate with very low and unreliable rainfall averaging about 230 mm/year. Most rainfall takes place during the months of December to March.

In the past, several local-scale studies have been carried out to assess the sustainability and the quality of the groundwater supplies at the aboriginal communities in the Musgrave Province. However, to date a detailed holistic study of the hydrogeology and groundwater resources of the Musgrave Province has not been carried out. This desk top hydrogeological evaluation of the Musgrave Province was carried out under the G-FLOWS (Goyder Facilitating Long Term Outback Water Solutions) initiative of the Goyder Institute for Water Research, and is based on a review of the existing literature and analysis of the bore data to better define the hydrogeology of the Musgrave Province. The hydrogeological data relevant to this study were mostly sourced from the various South Australian Government online databases.

There have been several studies of the geology of the Musgrave Province in the past. The Musgrave Province is structurally subdivided into the Mulga Park and the Fregon Subdomains consisting mainly of the amphibolite and granulite facies gneisses. The Mulga Park Subdomain covers a small area in the north, while the Fregon Subdomain occupies the remaining part in the south. The Musgrave Province has been intruded by mafic – ultramafic dykes and granitoids, and swarms of dolerite dykes. While basement outcrops occur as ranges at several places (reaching elevation of 1435 m Australian Height Datum at Mt Woodroffe), the remaining area is covered by sand dunes and thin desert sediments. The Officer Basin lies at the southern boundary of the Musgrave Province and contains clastic sediments of Adelaidean to Devonian age. There is a well developed palaeovalley system incised into the bedrock in the Musgrave Province. The Quaternary sand dunes (and at some locations, calcrete) are found overlying the bedrock terrain and the palaeovalley sediments. The Quaternary fluvial outwash occurs near the margin of the Musgrave Ranges.

Groundwater in the Musgrave Province occurs in the weathered and fractured sections of the Precambrian bedrock, palaeovalley sands, calcrete and the surficial sediments consisting of alluvial, fluvial and aeolian deposits. The hydrogeological data for the Musgrave Province is summarised for each aquifer in Table S1.

Table S1. Bore data summary for each type of aquifer in the Musgrave Province. SWL is the standing water level in the bores in metres below the natural surface, and the TDS is the total dissolved solids.

Aquifer	Mean depth of bores	SWL	Salinity (mean)	Salinity (median)	Mean bore yield	Median bore yield
	m	m bns	mg/L TDS	mg/L TDS	L/s	L/s
Alluvial/Fluvial	34.2	14	2579	870	1.39	0.75
Calcrete	78.2	15.5	2767	869	1.98	0.90
Palaeochannel	50.0	16.0	4500	1591	1.17	0.81
Aeolian	54.3	16.0	2118	1045	1.38	1.14
Officer Basin sediments	52.6	28.8	2983	1461	0.69	0.5
Fractured rock	36.3	11.5	2287	1133	0.55	0.24

Recharge for the study area has been estimated as part of a separate task of the G-FLOWS project. The estimated recharge rates are generally very low in the study area (<1 mm/yr) due to low rainfall, the perennial/tree vegetation and the soil types. Additional localised recharge may take place below ephemeral water bodies. An earlier study using carbon-14 and chlorine-36 radioisotopes has shown the recharge can vary from 10 mm/yr to 30 mm/yr near the Musgrave Ranges, and mostly occurs as a result of short intense rainfall events.

The groundwater flow pattern in the Musgrave Province has been studied from the limited available data. There are only a limited number of bores that have information on the watertable elevation in the Musgrave Province, particularly in the western part. The watertable elevation is generally sub-parallel to the topography, ranging from around 800 m AHD (Australian Height Datum) in the north and decreasing to around 350 – 420 m AHD in the south and southeast. Groundwater originates from rainfall recharge in the areas of higher elevation and flows under gravity toward the areas that are lower in topography such as watercourses. A hydraulic gradient of about 0.0015 is estimated for the eastern part of the Musgrave Province from the watertable elevation contours where sufficient water level data exist.

A salinity distribution map has been prepared and colour coded for the aquifer intersected in the various bores for the Musgrave Province. Groundwater is either fresh or marginally brackish with lower salinity groundwater occurring near the granite and gneiss outcrops due to recharge from the concentration of runoff over the rocky outcrops. The median salinities of the groundwater in the different aquifers are generally less than 1500 mg/L (Table S1). The groundwater salinity in the palaeochannels varies from 500 to >10,000 mg/L.

Previous studies on groundwater quality in the Musgrave Province reported that significant number of bores had salinity, nitrate and fluoride exceeding the guideline threshold values at several aboriginal communities. There have also been reports of significant bacteriological (Coliform) contamination in the community water supply bores.

The groundwater prospects in the Musgrave Province depend on the aquifer types and its saturated thickness. Yields in the surficial alluvial and aeolian sediments will depend largely on the saturated thickness of the sediments and the predominant lithology. Localised groundwater supplies may be obtainable from the fractured and weathered profile in the basement rocks. Geophysical maps such as Total Magnetic Intensity (TMI) may be able to identify lineaments and shear zones that could be useful for bore siting.

There appears to be a greater potential for groundwater supplies from palaeochannels and calcrete in the Musgrave Province where bore yields of up to 1000 kL/day have been recorded, however the data is probably based on short term tests at the time of drilling and does not represent the long-term flow from aquifers. Calcrete may display karstic features from which higher yields of groundwater may be sourced. The groundwater in calcrete can have a wide variation in salinity (600 to 25,000 mg/L) depending on its location within the flow system, with those in the lower reaches are likely to have higher salinity. Average bore yields in calcrete are the highest in the region at about 180 kL/day, however, yields of up to 250-1000 kL/day have been observed in some bores. The average yield of wells in the palaeochannel sediments is about 100 kL/day with some bores having yields of up to 600 kL/day. Most palaeochannel bores in the Musgrave Province have salinities less than 3000 mg/L. The sandstone and shale of the Officer Basin sediments in the southeastern margin of the study area may offer some groundwater potential that would need to be further assessed.

The estimated recharge to groundwater of <1 mm/yr (<60 ML/yr) is significantly lower that the current level of abstraction in the region (382 ML/yr). Hence, large-scale groundwater abstraction will likely cause a depletion of the groundwater resource. The historical water level trends in the aboriginal communities bores show that the wells in Amata, Pukatja, Umuwa and Yunyarinyi communities all have declining water levels due to the abstraction being in excess of the sustainable yields. The potential for large-scale groundwater supplies in the Musgrave Province has not been investigated on a regional scale, apart from low yielding fresh groundwater supplies for the aboriginal communities. So far there has been no study of the aquifer sustainable yields. A detailed groundwater investigation programme involving drilling and testing is required for the establishment of well fields and obtaining large-scale groundwater supplies.

ACKNOWLEDGMENTS

This hydrogeological study was carried out with funding from the Goyder Institute of Water Research and the CSIRO Water for a Healthy Country Research Flagship. The hydrogeological data relevant to this study were mostly sourced from the South Australian Government online databases. The author is grateful to Neil Power of the SA Department for Environment, Water and Natural Resources for making available unpublished hydrogeological reports for the Musgrave Province. The author would like to thank Tim Munday and Ian Jolly for conducting a review of this report and providing valuable feedback. The GIS and drafting support for this study was provided by Tania Abdat.

1 INTRODUCTION

1.1 Background

Planned and potential mining and energy development in South Australia's far north is set to have significant consequences for the water resources of the region. These sectors generate significant economic value to the State and their support remains a priority for the government. The scale of the planned developments and the potential from current exploration programs facilitated by the South Australian Government through the *Plan for Accelerated Exploration* (PACE) Program will result in a substantial increase in infrastructure requirements, including access to water resources and Aboriginal lands for exploration and potential mine developments.

Presently, knowledge about the character and variability of groundwater resources, the sustainability of this resource, and its relationship to environmental and cultural assets remains very limited, particularly in the priority areas for development as defined by the Department for Manufacturing, Innovation, Trade, Resources and Energy (DMITRE). These areas include the Musgrave Province and the Anangu Pitjantjatjara Yankunytjatjara (APY) Lands in the State's far North. In this region, access to water is recognised as a key infrastructure requirement for potential mining and energy development. Presently, knowledge about the character and variability of the area's groundwater resources, the sustainability of this resource, and its relationship to environmental and cultural assets remains very limited. To address this, in part, a holistic review of the hydrogeology and groundwater prospects of the region was undertaken.

This study was carried out under auspices of the Goyder Institute for Water Research FLOWS (Facilitating Long Term Out-back Water Solutions) project with the prime purpose of better defining the groundwater resources in this priority area.

1.2 Location

The Musgrave Province comprises a crystalline basement that extends across the South Australian, Western Australian and Northern Territory borders. In South Australia it occupies an area of about 60,000 km^2 in the north western part of the state (Major and Conor, 1993) and is bounded by latitudes 26°S and 28°S and longitudes 129°E and 134°E. The region is covered by the MANN, WOODROFFE, ALBERGA, ABMINGA, BIRKSGATE, LINDSAY and EVERARD 1:250,000 map sheet areas (Figure 1). The area of the Musgrave Province extends 500 km in the east – west and about 200 km in the north-south direction within the South Australian sector.

The Musgrave Province has significant potential for nickel. Potential also exists for base metals, gold and copper (Rankin and Newton, 2002) however, exploration for these commodities has been limited due to lack of data and access.

There is no major town that services the area. However, the province includes the Anangu Pitjantjatjara Yankunytjatjara (APY) Lands and is home to several aboriginal communities.

1.3 Previous studies

Reports on several studies carried out in the past have provided valuable information on the geology, hydrogeology and the groundwater resources of the Musgrave Province. Regional geology has been described by Major and Conor (1993) as part of "The geology of South Australia" bulletin of the SA Geological Survey. The geology of the Musgrave Province has also been described in Gum and Conor (2003) as part of "The South Australian mineral explorers guide". The regional geology has also been summarised by Rankin and Newton (2002) together with the interpretation of airborne magnetic data as part of a joint Rio Tinto Exploration and Primary Industries and Resources (SA) study. In addition, the several 1:250,000 scale maps and explanatory notes (e.g. Mirams, 1963) provide information on the surface geology of the Musgrave Province.

The calcrete of the Musgrave Province has been studied by Chen et al. (2002) in which various geological and soils maps of different scales were compiled to produce a map showing the distribution of regolith carbonates. Palaeochannel mapping of the Musgrave Province were compiled by Hou et al. (2007) and its hydrogeology was discussed in Magee (2009) and Lewis et al. (2010) as part of the 'Raising National Water Standards Project: *Water for Australia's arid zone – Identifying and assessing Australia's palaeovalley groundwater resources* that was based on desk-top studies.

A comprehensive regional hydrogeological assessment for the Musgrave Province, is lacking, with only a few regional studies carried out (e.g. GHD, 2009b). More recently Watt and Berens (2011) have produced a report that provides a thorough review of the various studies related to the hydrogeology and groundwater resources of the region. Several local-scale studies have been carried out for the sustainability and the quality of the groundwater supplies at the aboriginal communities in the Musgrave Province e.g. Fitzgerald et al. (2000), Dodds et al. (2000, 2001a, 2001b), AGT (2003, 2008) and GHD (2009a & b). To-date a more detailed, regional perspective of the hydrogeology and groundwater resources of the Musgrave Province has not been carried out, and this report aims, in part, to address that.

1.4 Data collection

This study is based on a review of the existing literature and analysis of the bore data to better define the hydrogeology of the Musgrave Province. The hydrogeological data relevant to this study were mostly sourced from the following South Australian Government online databases.

Drillhole Enquiry System (**https://des.pir.sa.gov.au/deshome.html**) – Drillhole data including bore location, depth, construction details, static water level, salinity and lithological logs.

Obswell (**https://obswell.pir.sa.gov.au/new/obsWell/MainMenu/menu**) – Well, level and salinity data for observation networks .

SARIG (**https://sarig.pir.sa.gov.au/sarig/frameSet.jsp**) – DMITRE's Resources Information Geoserver for Information on geological and groundwater basin maps, mining tenements and other land use, and topography.

Bore data availability for the Musgrave Province is shown in Figure 2. There are just over 1400 bores in the Musgrave Province which have information regarding bore depths. There are approximately 406 bores which have static water level data, of these around 313 have water levels that are referenced to a datum (Australian Height Datum). There are 589 bores that have salinity data. About 532 bores have information regarding bore yields. The average depth of the bores is about 30 m with most bores having depths between 10-50 m. The information on the type of strata intersected was available from only 290 bores. There are currently ~40 bores that are regularly monitored by the SA Department for Water as part of the PITLANDS Obswell network. The purpose of this monitoring is to ensure adequate water supplies for the aboriginal communities in the APY lands.

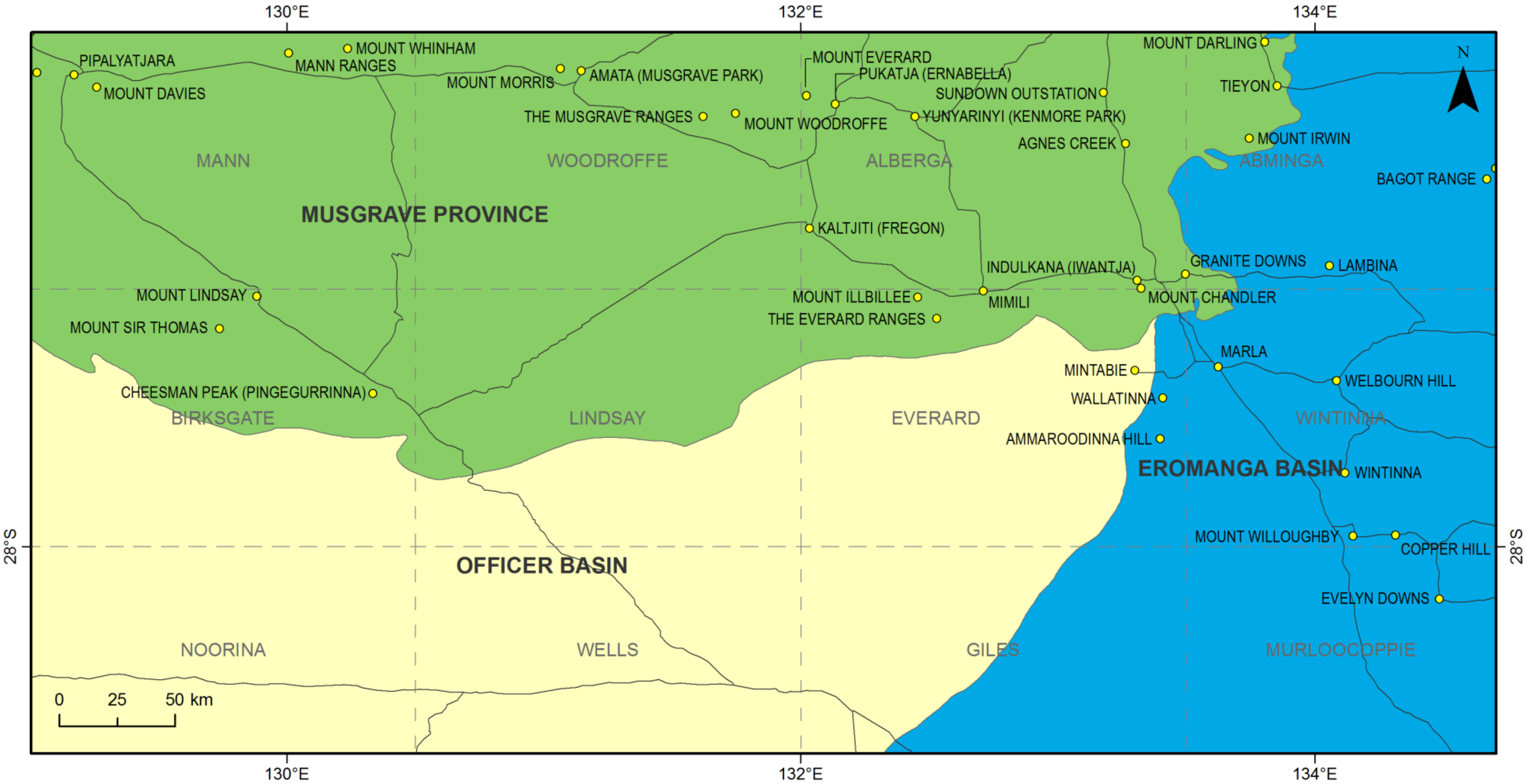

Figure 1: Location of the study area showing the Musgrave Province, aboriginal communities and road access.

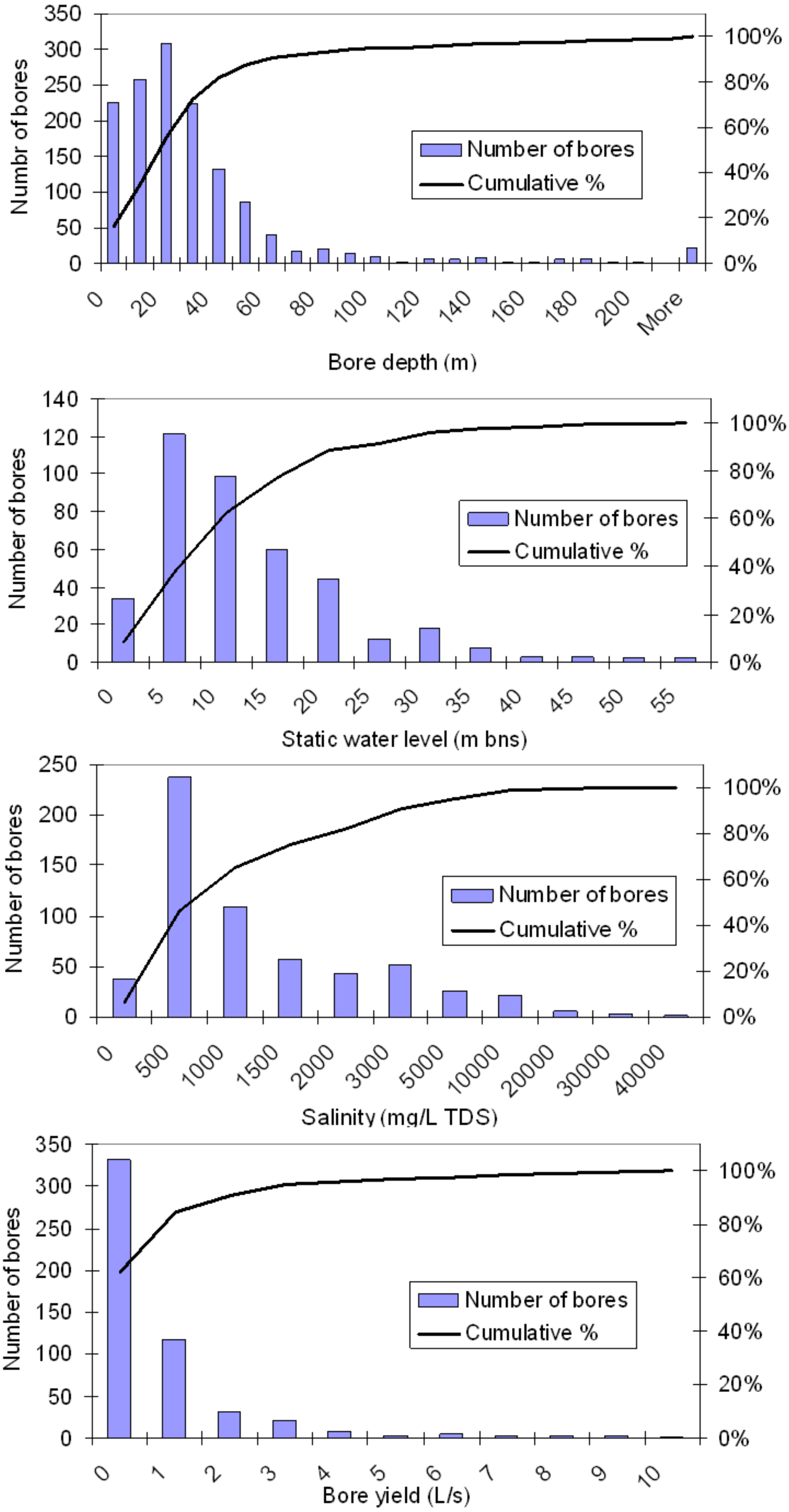

Figure 2: Bore data availability in the Musgrave Province.

2 REGIONAL SETTING

2.1 Topography and drainage

The topography and drainage of the Musgrave Province is shown in Figure 3. The northern part of the region is occupied by the rugged hilly terrain of the Mann and the Musgrave Ranges with Mt Woodroffe reaching an elevation of 1435 m AHD (Australian Height Datum). The Birksgate and the Everard Ranges occur to the south. The topographical elevations decrease to around 350-400 m AHD towards the south and the southeast of the area where wide calcrete plains occur and are often covered by aeolian deposits of sand dunes. The Great Victoria Desert to the south of the northern ranges is covered by sand plains and dune fields (Watt and Berens, 2011).

The dunes typically trend NW-SE in the Musgrave Province and reach up to 30 m in height. In the eastern parts, however, the sand dunes are more isolated and generally trend east-west with some NE-SW trending dunes occurring in the northeastern margin of the region.

Compared to the west, there is a well defined drainage in the eastern part of the Musgrave Province with several ephemeral creeks originating in the Musgrave Ranges that eventually flow southwards into the Officer Basin (Officer Creek) or into the Alberga River. In the west the creeks are restricted to the hilly terrain and terminate in alluvial outwash areas on the margins of the extensive flats (Mirams, 1963).

2.2 Climate

The Musgrave Province has a semi-arid climate with very low and unreliable rainfall averaging about 230 mm/year. Most rainfall takes place during the months of December to March. December has the highest average rainfall of around 30 mm/year. Rainfall record for Pukatja (formerly known as Ernabella) (Figure 4) in the region shows a rising trend in the annual rainfall. The record also depicts several short-term cycles during which the annual rainfall is mostly above or mostly below the long-term average. The current increasing trend in the average rainfall is part of a longer cycle. The region has a very high evaporation rate with the average annual pan evaporation ranging between 2800 and 3400 mm (Source: Bureau of Meteorology).

August has the lowest average monthly rainfall of 8.5 mm/year. Winter months are May to August when mean temperatures range between 3.7°C and 20.2°C. January is the hottest month with a mean maximum temperature of 37.8°C (Source: Bureau of Meteorology).

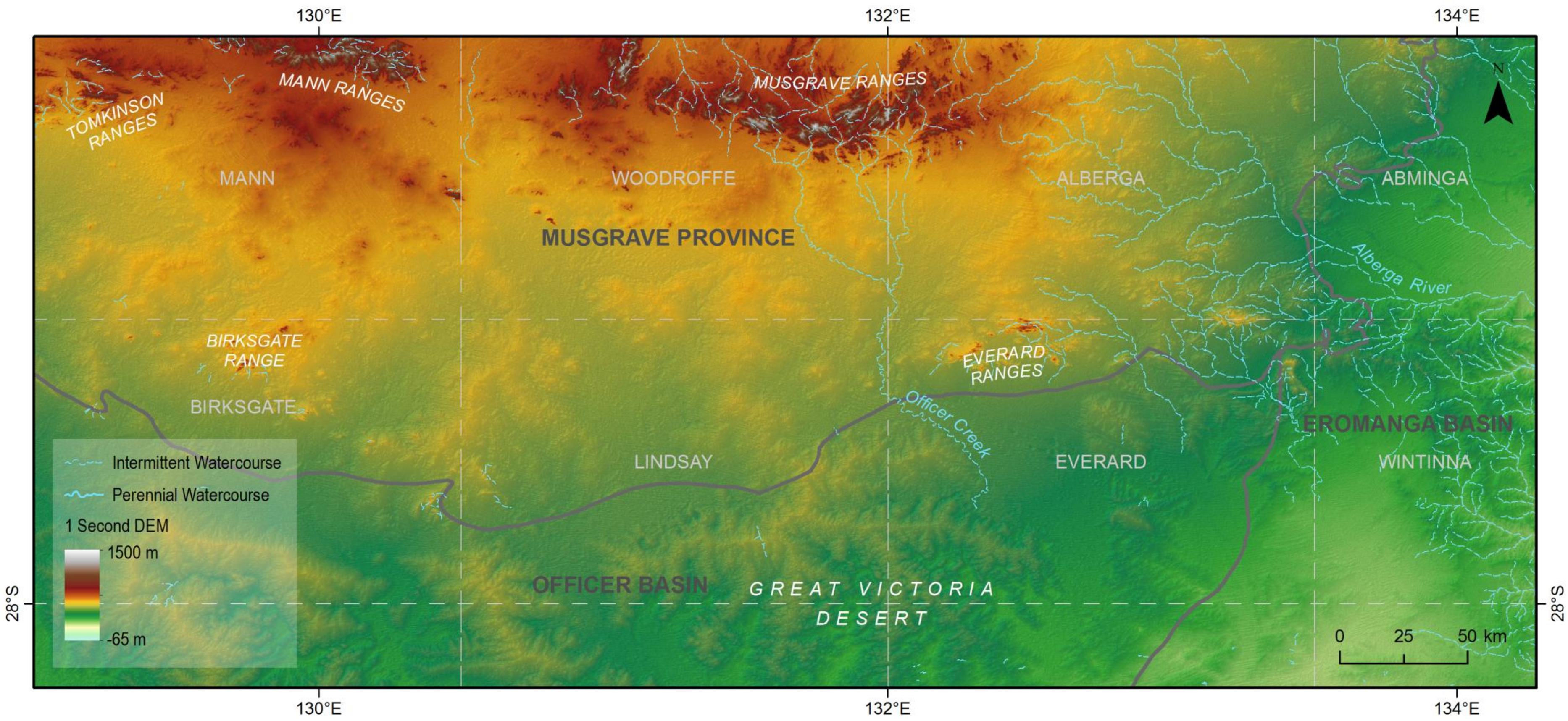

Figure 3: Topography and drainage of the Musgrave Province.

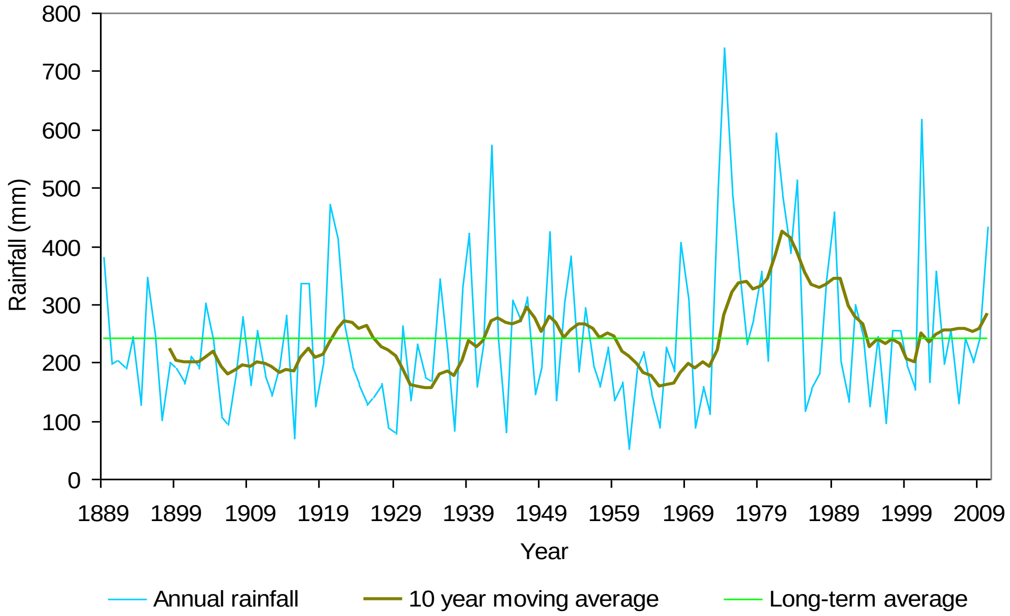

Figure 4: Musgrave Province rainfall (Source: SILO patch point data for Pukatja).

3 GEOLOGY

The geology of the Musgrave Province has been described in Major and Conor (1993), Rankin and Newton (2002) and Gum and Conor (2003). The region's basement is structurally subdivided into the Mulga Park Subdomain and the Fregon Subdomain consisting mainly of the amphibolite and granulite facies gneisses.

The Mulga Park Subdomain covers a small area in the north, while the Fregon Subdomain occupies the portion in the southern part separated by the Woodroffe Thrust within the South Australian state boundary (Figure 5). The Fregon Subdomain is mostly comprised of the gneiss of the Birksgate Complex. The Musgrave Province, or Block as it is sometimes called, has been intruded by mafic – ultramafic dykes of the Giles Complex and granitoids belonging to the Kulgera Suite, and swarms of dolerite dykes.

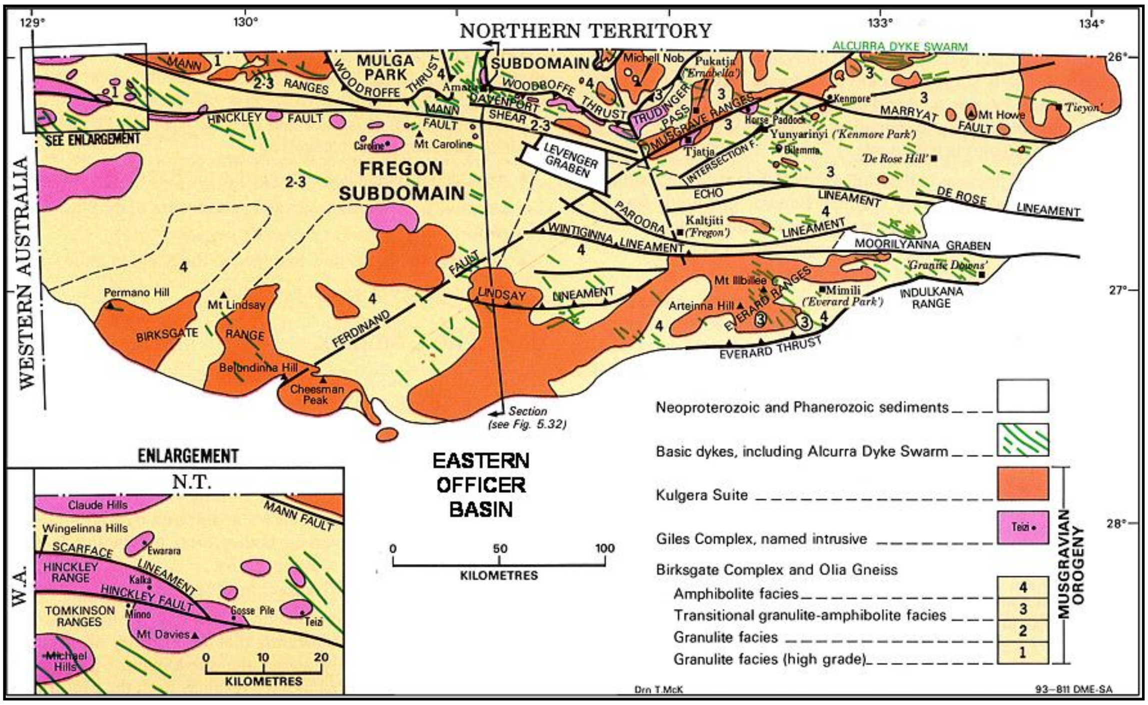

Figure 5: Geology of the Musgrave Province (Major and Conor, 1993)

While basement outcrops occur as ranges at several places, including the Mt Woodroffe which is the highest point in South Australia, the remaining area is covered by sand dunes and thin desert sediments.

A series of east-west trending faults and lineaments have been defined across the region. The Woodroffe Thrust, Davenport Shearzone and the Mann, Ferdinand Hinckley, Marryat and the Scarface Faults being the more important ones.

The Officer Basin lies at the southern boundary of the Musgrave Province and contains clastic sediments of Adelaidean to Devonian age. The basin does not onlap on the Musgrave Province, but is sharply truncated by the overthrust Musgrave Province (Major and Conor, 1993).

There is a well developed palaeovalley system incised into the bedrock of the Musgrave Province occurring across the sand covered plains (Lewis et al., 2010). These palaeovalleys are filled with Tertiary sediments comprising clay, sandy clay and minor coarse sand and gravel. The Quaternary sand dunes and at places calcrete are found overlying the bedrock terrain and the palaeovalley sediments. Apart from the palaeovalleys, Quaternary fluvial outwash occurs near the margin of the Musgrave Ranges.

4 HYDROGEOLOGY

4.1 Groundwater occurrence

Groundwater in the Musgrave Province occurs in the weathered and fractured sections of the Precambrian bedrock, Pliocene to Pleistocene palaeovalley sands, Pleistocene calcrete and the Holocene surficial sediments consisting of alluvial, fluvial and aeolian deposits. The surface occurrence of these units is shown in Figure 6. A summary of bore data from each of the 1:250,000 Map areas are provided in Table 1. Data are also summarised for each aquifer in Table 2.

Table 1: Summary of bore data in the Musgrave Province for each of the 1:250,000 map areas.

Map Area	Bores	Mean depth	Median depth	Maximum depth	Depth to watertable	Mean Salinity	Median Salinity
		m	m	m	m bns	mg/L TDS	mg/L TDS
Alberga	819	28	23	366	13.2	3095	1308
Birksgate	34	54	48	139.5	28.0	5570	1085
Everard	88	53	22	1083.5	16.5	2530	1266
Lindsay	27	40	42	67	22.5	1584	1068
Mann	300	61	40	776	16.7	1264	750
Woodroffe	203	48	30	489	12	1465	900

bns: below natural surface; TDS: Total dissolved solids

Table 2: Bore data summary for each type of aquifer in the Musgrave Province.

Aquifer	Mean depth of bores	SWL	Salinity (mean)	Salinity (median)	Mean bore yield	Median bore yield
	m	m bns	mg/L TDS	mg/L TDS	L/s	L/s
Alluvial/Fluvial	34.2	14	2579	870	1.39	0.75
Calcrete	78.2	15.5	2767	869	1.98	0.90
Palaeochannel*	50.0	16.0	4500	1591	1.17	0.81
Aeolian	54.3	16.0	2118	1045	1.38	1.14
Officer Basin sediments#	52.6	28.8	2983	1461	0.69	0.5
Fractured rock	36.3	11.5	2287	1133	0.55	0.24

*Based on intersection of bore data and palaeochannel map in GIS (Hou et al., 2007)
#In the south east of the study area

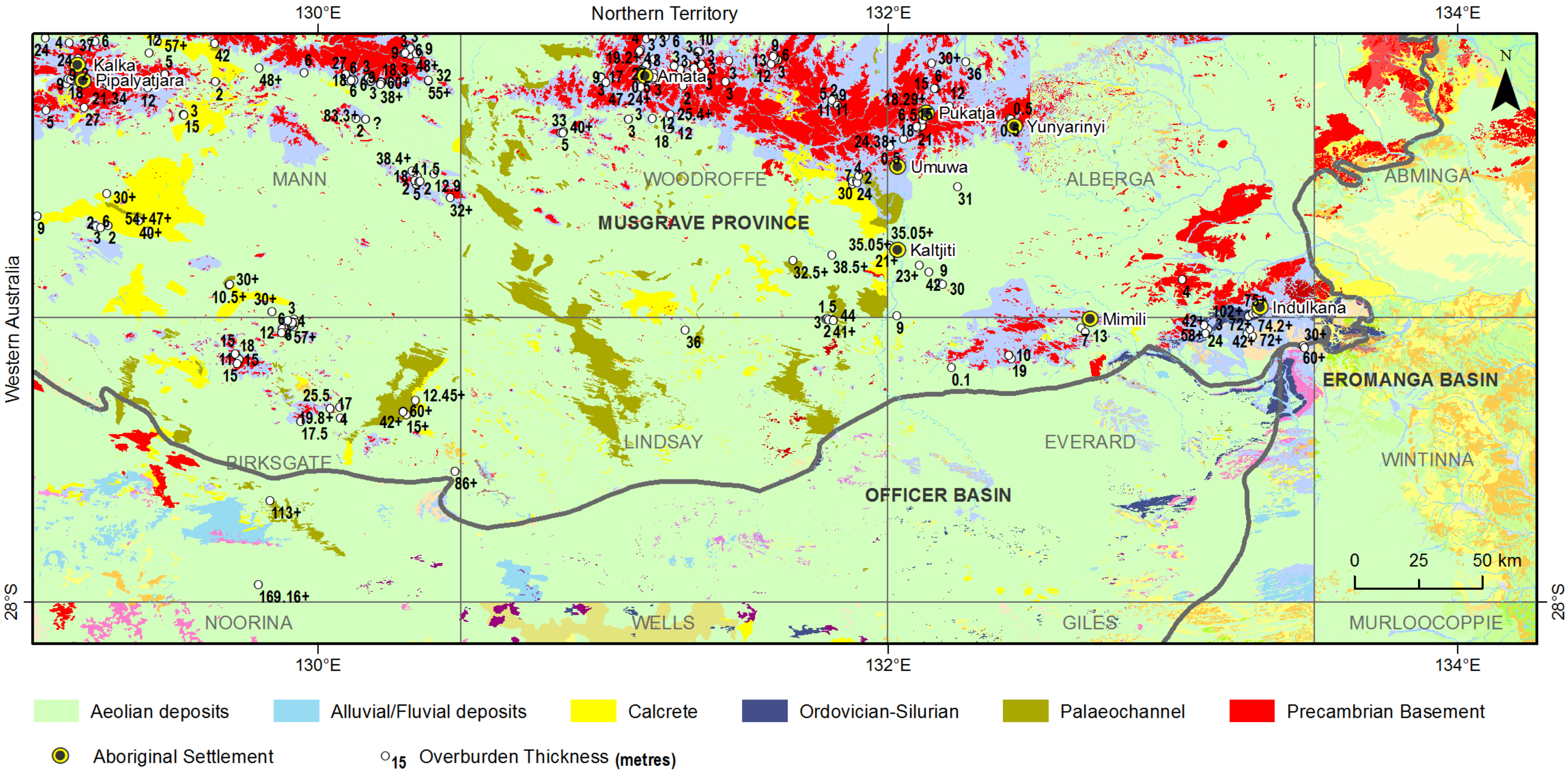

Figure 6: Surface map of the principal hydrogeological units of the Musgrave Province showing the overburden thickness (m) where available. Modified from the surface geology GIS data obtained from SARIG, South Australia.

The surficial sediments generally consist of a mixture of sand, clay, gravel and limestone overlying the basement granite and gneiss. The thickness of the surficial sediments ranges between less than 5 m to 50 m with an average of around 35 m. However, in the southern part of the region further away from the outcropping basement, the sediment thickness can be as much as 80 m or more. The depth to water is in the range of 10-20 m and the average saturated thickness of the sediments is around 20-30 m. Mean bore yields in the surficial sediments are around 120 kL/day.

Groundwater in the Musgrave Province also occurs in calcrete defined as "...near surface, terrestrial, accumulation of predominantly calcium carbonate, which occurs in a variety of forms from powdery to nodular to highly indurated..." (Wright and Tucker, 1991 *in* Chen et al., 2002). The thickness of calcrete can range from tens of centimetres to tens of meters and it can be interbedded with sediment layers (Chen et al., 2002). Across the Musgrave Province the sequence of calcrete and sediments are on an average about 30 m thick. The region has an abundance of calcrete deposits some of which are >100 km^2. The average depth to the watertable is about 17 m in calcrete. Mean bore yields are the highest of all of the aquifer types (around 170 kL/day).

The palaeochannels of the Musgrave Province have been mapped by Hou et al. (2007) as shown in Figure 7. The palaeochannels were originally formed in the wetter climate of the Palaeogene and are filled mostly with clay, sandy clay and minor lenses of coarse sand and gravel and are commonly associated with near surface calcrete deposits (Lewis et al., 2010). Bores drilled in the palaeovalleys for which lithological information is available, intersected an average of at least 50 m of the palaeovalley sediments, although an interpretation of airborne electromagnetic data over parts of the Province indicates thicknesses >150 m in places. The average depth to the watertable is about 16 m in the palaeochannels and mean bore yields are around 100 kL/day. Hydrogeological sections near palaeochannels showing the palaeochannel sediments and the depth to the basement are shown in Figure 8 and Figure 9.

The weathered and fractured granites and gneiss also contain groundwater in the Musgrave Province. The average thickness of the weathered zone is usually about 10 m and overlies about 15 m of the fractured rock. The static water level is about 8 m deep in these areas and mean bore yields are very low at around 50 kL/day. The Mt Chandler Sandstone of the Officer Basin occurs in the southeastern margin of the Musgrave Province and consist of massive sandstone, quartzite and shale of Ordovician age of around 150 m in thickness (Coats, 1963). Bores in this area have intersected an average of 52 m of the sediments (maximum 103 m). The SWL is about 36 m deep on average in these sediments. The average salinity of the groundwater in these sediments is around 1500 mg/L. Mean bore yields are around 60 kL/day from fractured sandstone. However, higher yields of around 180 kL/day have been intersected.

4.2 Recharge

Recharge for study area has been estimated in Task 6 (Groundwater recharge characteristics across key priority areas) of the G-FLOWS project using the Method of Last Resort (MOLR) technique (Crosbie et al., 2010a), but using more recent regressions (Ian Jolly, pers. comm., 2011). The estimated recharge rates are generally very low in the study area (<1 mm/yr) due to low rainfall, the perennial/tree vegetation and the soil types. However, this estimate is for diffuse rainfall recharge, and additional localised recharge may take place below ephemeral water bodies. Task 6 of the G-FLOWS project has also used the Groundwater Chloride Mass Balance technique (see Crosbie et al., 2010b for a description of the technique) to estimate recharge in the study area and found rates as high as 29 mm/yr which are indicative of localised recharge (Ian Jolly, pers. Comm., 2012). Furthermore, there are several reports (e.g. Dodds and Sampson (2000, 2001) *in* Lewis et al. (2010) and GHD (2009)) that mention that periodic heavy rainfall events are likely to be more significant in terms of groundwater recharge. These reports made note of rises in community bore water levels of 3-4 m after large rainfall events.

The alluvial sediments close to the Mann and Musgrave Ranges are likely to receive greater recharge due to concentration of runoff over the basement outcrops. This is reflected in the lower salinities of the groundwater in the alluvium near the basement outcrops (<1500 mg/L). A study of carbon-14 and chlorine-36 radioisotopes in the groundwater in the Musgrave Province by Cresswell et al. (2002) concluded that recharge varied from 10 mm/yr to 30 mm/yr near the Musgrave Ranges. The study suggested that recharge occurred as a result of short intense rainfall events.

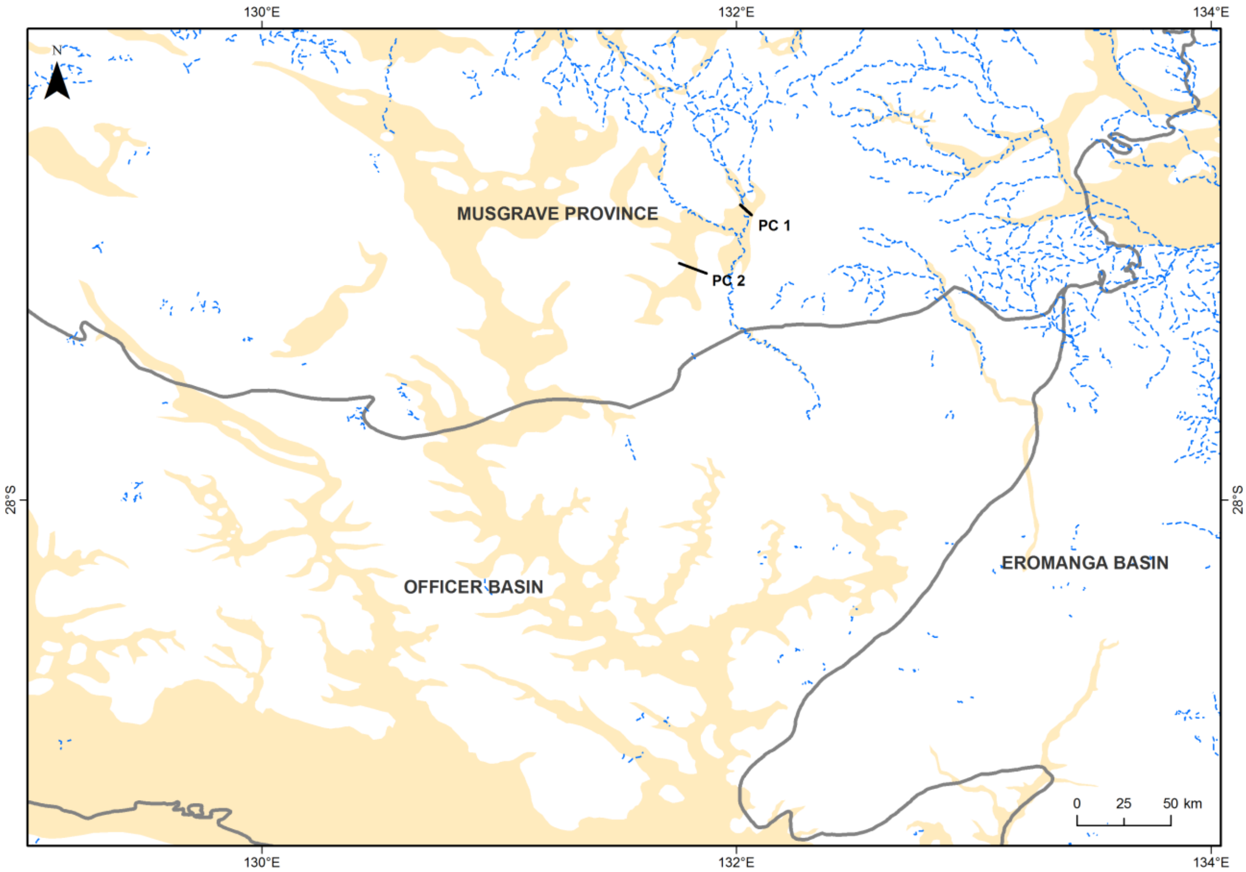

Figure 7: Palaeochannels of the northwestern part of South Australia (after Hou et al., 2007). The map also shows the present day drainage and the locations of hydrogeological sections PC1 and PC2, shown in Figures 8 and 9 respectively.

4.3 Groundwater flow

There are only a limited number of bores that have information on the watertable elevation in the Musgrave Province. In the west of the region, in the Mann and Birskgate 1:250,000 map areas in particular, there are several bores for which the static water level data (as depth from surface) exist, although most of these are not referenced to a datum. Figure 13 in GHD (2009a) shows a regional map of the depth to groundwater (SWL) as part of the water resources assessment for the Alinytjara Wilurara (AW) NRM region. The map shows the depth to the groundwater in the Musgrave Province ranging from <2 m to >50 m. However, such maps cannot be used for understanding the groundwater flow systems for which the SWL referenced to a datum is required. From the limited available data, the interpreted watertable elevation is generally sub-parallel to the topography, ranging from around 800 m AHD (Australian Height Datum) in the north and decreasing to around 350 – 420 m in the southern and southeastern parts of the region (Figure 10). Groundwater originates from rainfall recharge in the areas of higher elevation and flows under gravity toward the areas that are lower in topography such as watercourses. A hydraulic gradient of about 0.0015 is estimated for the eastern part of the Musgrave Province where sufficient water level data (reduced to AHD) is available. As there is no information on the permeability of the aquifers, an estimate of throughflow could not be carried out.

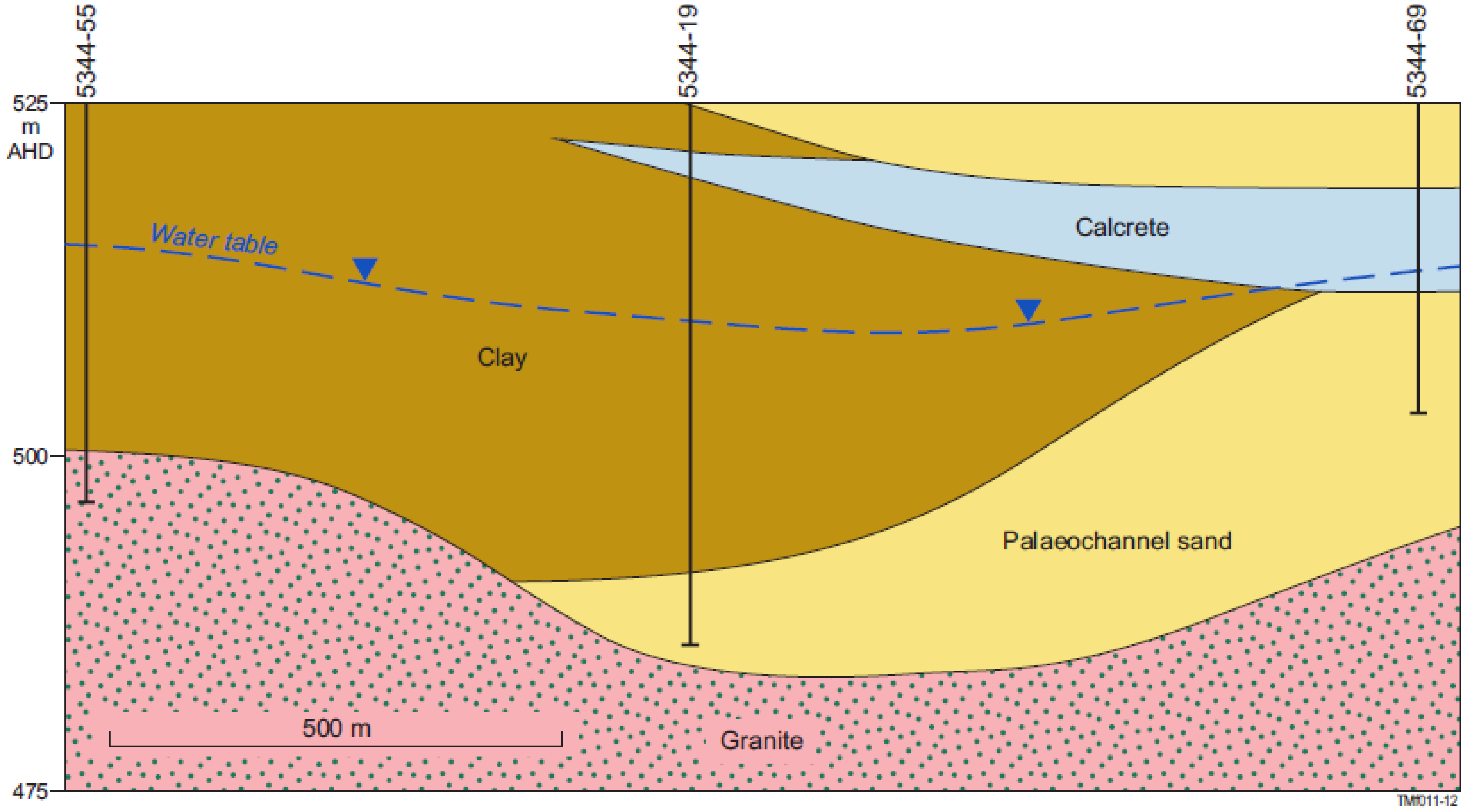

Figure 8: Hydrogeological sections near a palaeochannel (PC1) showing the channel sediments and the watertable. Section location is shown in Figure 7.

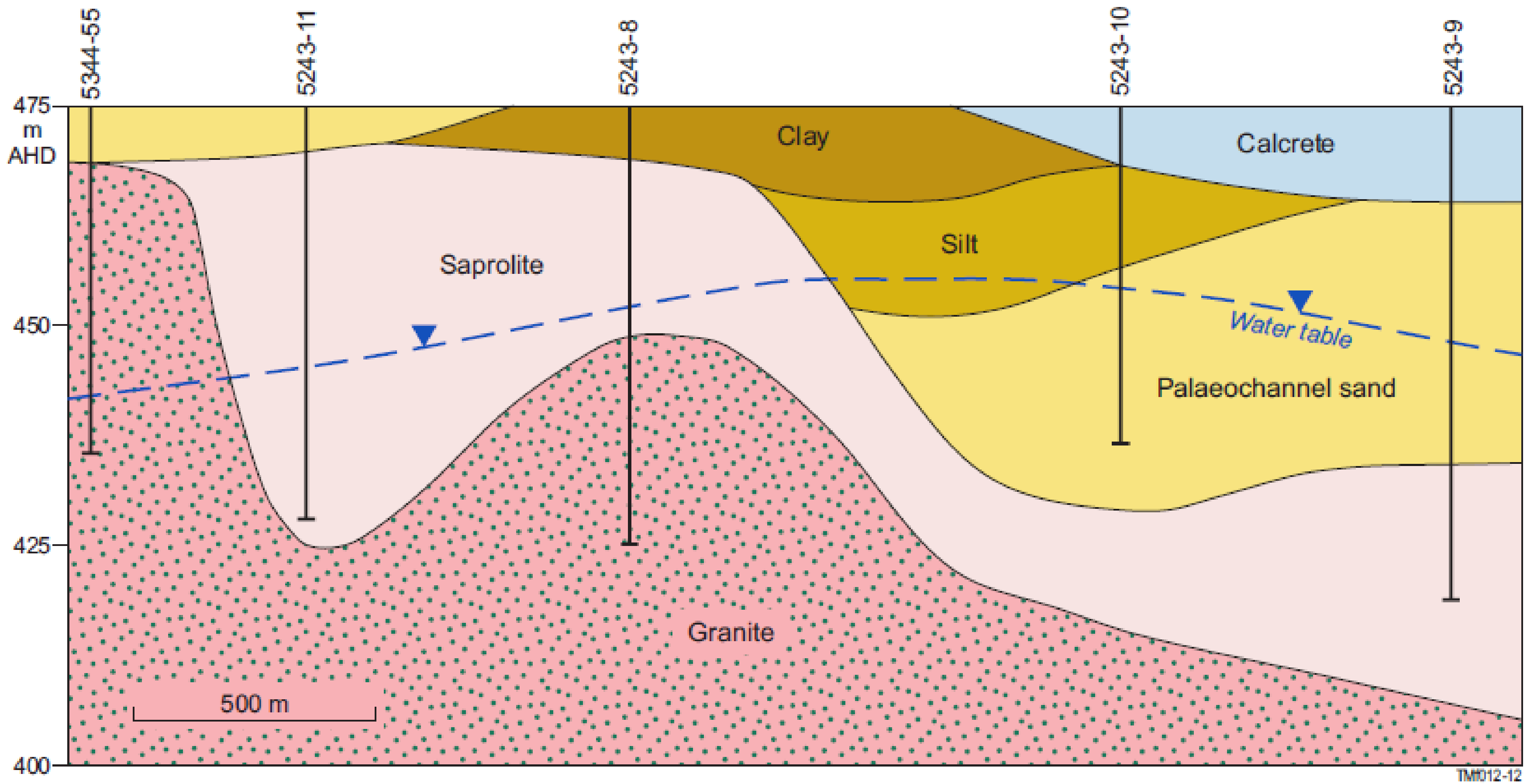

Figure 9: Hydrogeological sections near a palaeochannel (PC2) showing the channel sediments and the watertable. Section location is shown in Figure 7.

Groundwater discharge takes place from basement rock aquifers into the palaeochannels and surficial sediment aquifers, and by throughflow into the Officer Basin sediments to the south, with minimal discharge taking place into the surface water features (GHD, 2009b).

4.4 Groundwater quality

Based on limited data, the groundwater salinity was previously contoured on a regional scale for the AW NRM Region by GHD (2009a), and this showed that the salinity in the Musgrave Province ranged from <1,500 to >30,000 mg/L. As a part of the current study, the salinity distribution has been mapped and colour coded for the aquifer intersected in the bores as shown in Figure 11. Lower salinity groundwater occurs near the granite and gneiss outcrops due to recharge from the concentration of runoff over the rocky outcrops. Groundwater in most bores drilled in the area is either fresh or marginally brackish. Table 1 summarises the average salinities for each of the 1:250,000 map areas. The median salinities of the groundwater bearing units are generally less than 1500 mg/L (Table 1 and Table 2). The large difference between mean and median salinity reflects the occasional extreme values of salinity. Higher salinity groundwater occurs in potential discharge areas such as low lying areas where evaporation from shallow watertable increases the concentration of salts (Figure 11). The groundwater salinity in the palaeochannels varies between 500 to >10,000 mg/L with a median salinity of around 1600 mg/L.

In the Musgrave Province the groundwater pH varies from 5.4 to 8.1 with an average of 7.5 (0.5 SD). GHD (2009b) reported that the nitrate and chlorine levels in the groundwater across the Musgrave Province commonly exceed the World Health Organisation (WHO) guidelines. Fluoride concentration was also reported to be above the guideline levels at Kaltjiti (formerly known as Fregon), Mimli, Yunyarinyi (formerly known as Kenmore Park) and Pukatja communities.

Fitzgerald et al. (2000) conducted a comprehensive water quality assessment in the remote communities in the Anangu Pitjantjatjara Lands, and reported that only about a quarter of the water bores (32 out 129) met all the requirements of the Australian Drinking Water Guidelines (1996) with significant number of bores having salinity, nitrate and fluoride exceeding the guideline threshold values. The report also noted significant bacteriological (Coliform) contamination in the bores, with *E. coli* bacteria found in a few bores. Subsequent to this study, the groundwater quality at each aboriginal community was reviewed and summarised by Dodds et al. (2001b). The review concluded that although 5 of the 9 communities investigated had groundwater that met the Australian Drinking Water Guidelines, the supplies at Iwantja, Mimili, Kaltjiti and Amata were marginal to unacceptable in terms of salinity, fluoride and boron. Microbiological contaminants were also found in many bores and it was recommended that these required further monitoring and treatment.

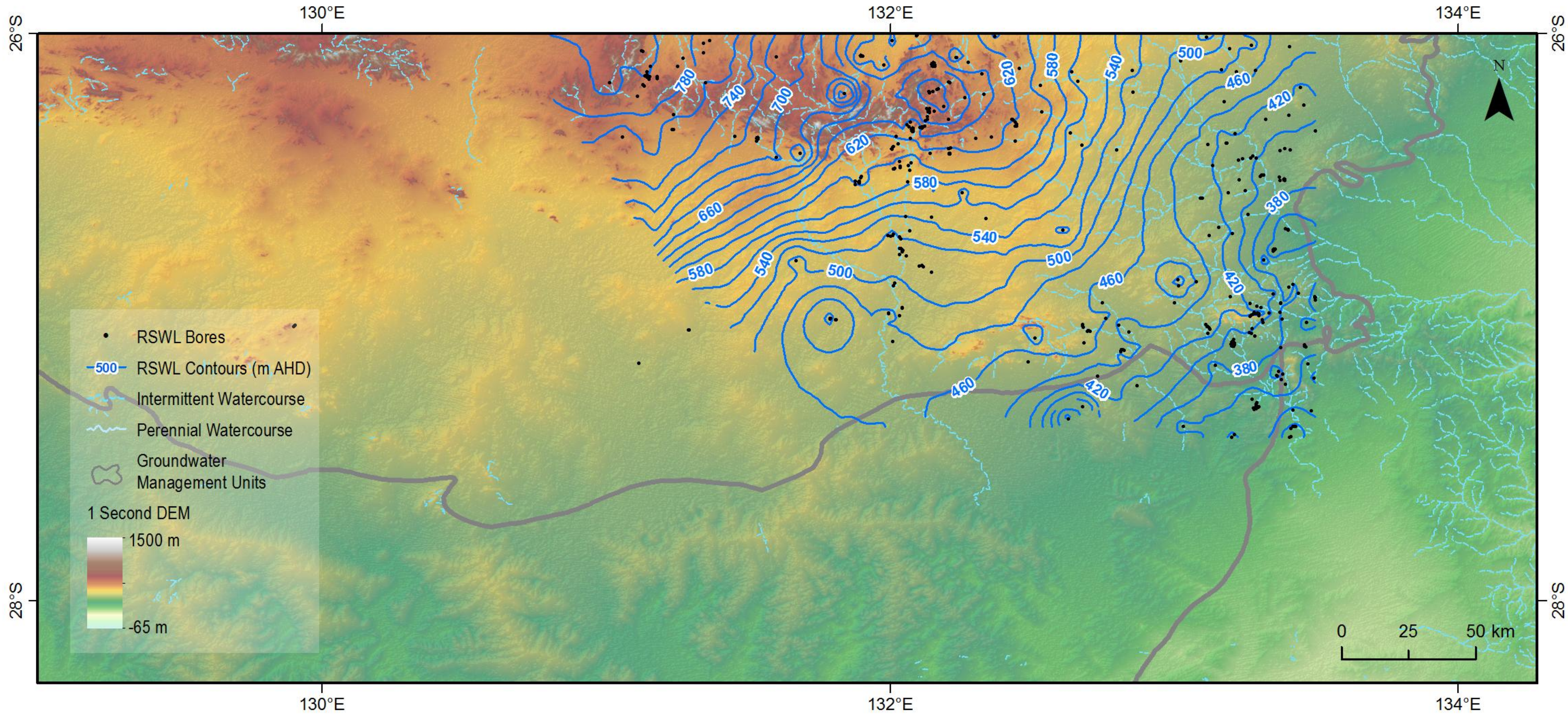

Figure 10: Regional watertable (RSWL) contours (m AHD) for the eastern Musgrave Province. Data density is shown as black dots. There is a lack of watertable elevation data in the western part. Groundwater flow is perpendicular to the contours. A watertable may not exist where basement outcrops occur unless they have laterally and vertically connected fractures that are saturated with groundwater.

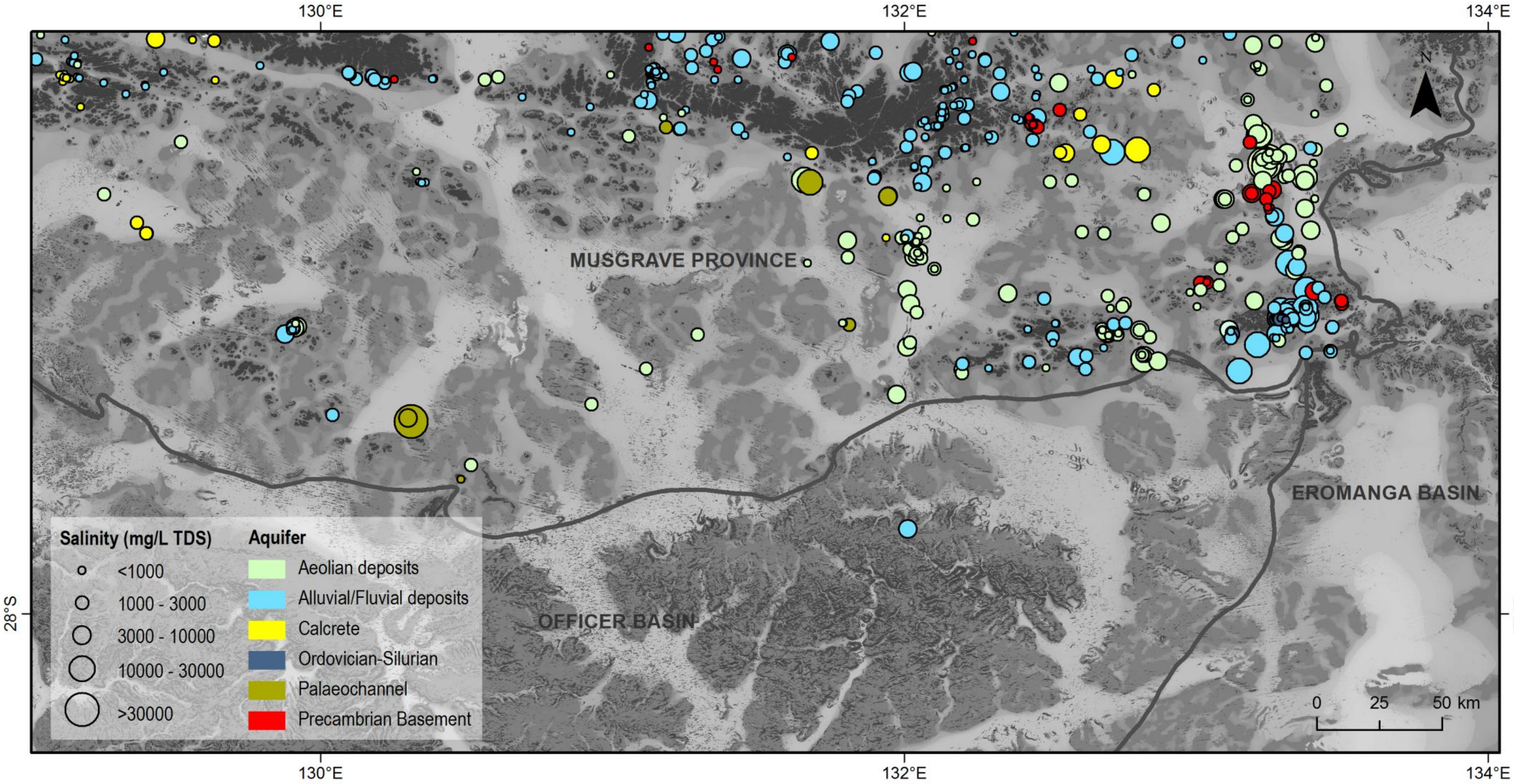

Figure 11: Groundwater salinity in the Musgrave Province, colour coded with respect to the aquifer intersected. The background map shows the surface of valley bottoms based on their topographic signature as flat low-lying areas based on MrVBF algorithm (Gallant and Dowling, 2003).

5 GROUNDWATER RESOURCES

5.1 Groundwater use and future demand

According to the DMITRE Drillhole Enquiry System database, groundwater is extracted from about 200 water supply bores in the Musgrave Province. The Musgrave Province is covered by the Mackay and Musgrave Groundwater Management Units (GMU). Groundwater use in these units is mostly for domestic and stock purposes, with mining and industrial being other potential uses (GHD, 2009b). The current groundwater use for the aboriginal community water supplies is estimated as 382 ML/yr (Australian Groundwater Technologies, 2010). The groundwater levels in bores at some of these communities are declining and the water quality in some bores are poor. This would necessitate investigations for additional good quality groundwater supplies at these communities.

Several studies regarding the sustainability of water supplies for the aboriginal communities have been carried out by Australian Groundwater Technologies (2003, 2008), however, a study on future demand for water supplies in the region has not yet been carried out. The South Australia's Water for Good strategic plan recommends development of regional water demand and supply plans that include assessments based on population growth, development by sector, environmental and sustainability issues including climate change impacts (Government of South Australia, 2009). There are several mineral exploration licenses granted and licenses applied for in the region which could create a new demand for water for facilitating mining activities in the future.

5.2 Groundwater potential

Groundwater in the Musgrave Province occurs in the surficial sediments comprising the alluvial and aeolian deposits; palaeochannel sands; calcrete; and the weathered and fractured rocks of the Precambrian basement as shown schematically in Figure 12. A regional watertable trend is indicated from the available bore data, although this may be absent in areas where the basement rocks outcrop in which fractures and hence groundwater may be absent. A watertable may also be absent over catchment divides.

The groundwater databases of the SA Government provide estimates of the groundwater yields that are mostly measured in bores at the completion of drilling using various methods such as airlift, pumping, etc. While the airlift yields indicate the short term flow rates in boreholes, they usually do not represent the long-term flow capacity of the aquifers. At times when initial higher yields of 5-15 L/sec (400-1300 kL/day) have been identified, they were found to decline to <2 L/sec within a year (GHD, 2009b).

Groundwater availability in the surficial alluvial and aeolian sediments will depend largely on the saturated thickness of the sediments and the predominant lithology. The thicknesses of the sediments can vary from <2 m near the areas of basement outcrops to about 50 m. Bores in the surficial sediments have an average (airlift) yield of 1.4 L/s (120 kL/day) with higher yields of up to 10 L/sec (860 kL/day) observed in some bores.

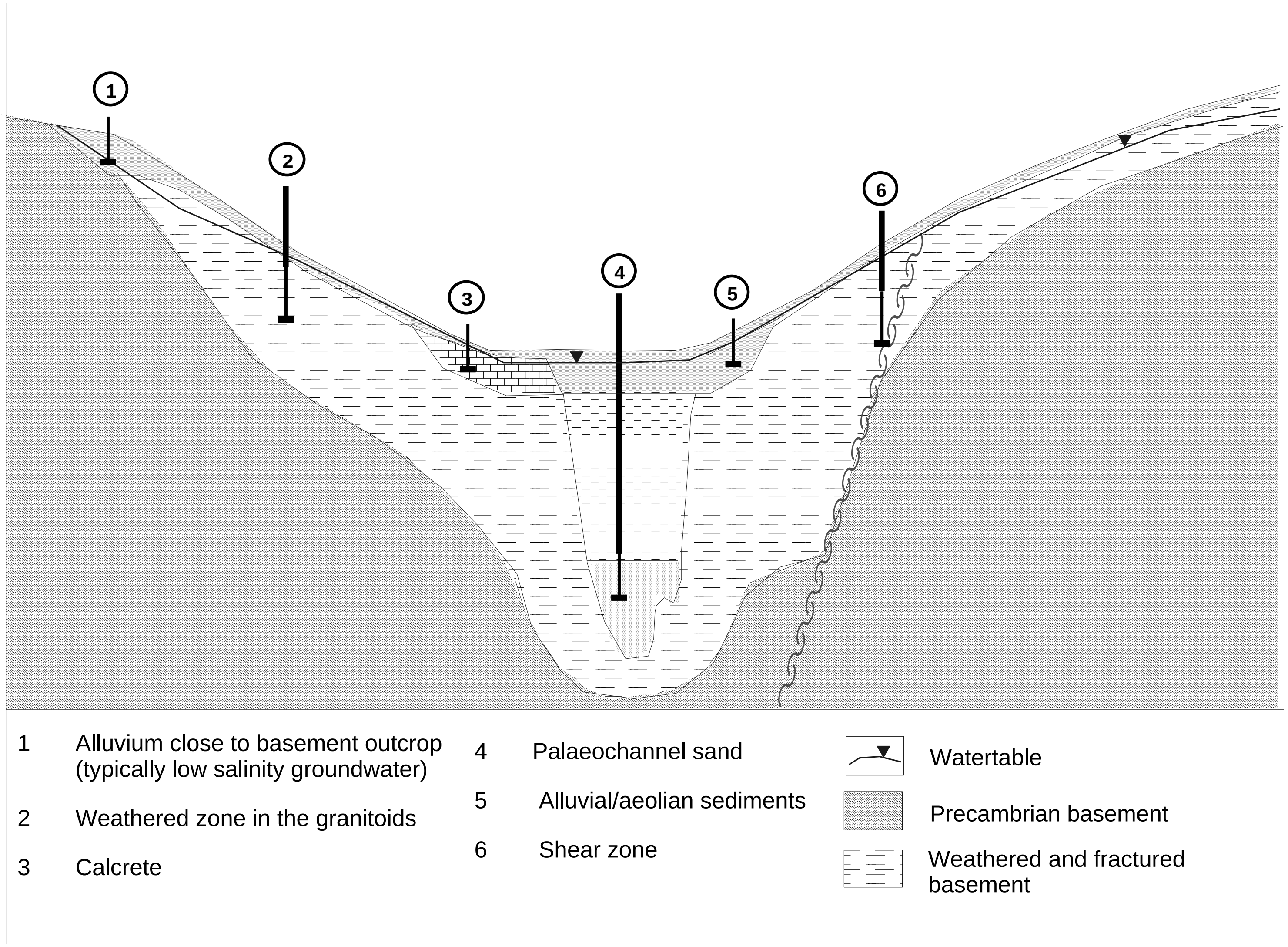

Figure 12: Schematic section showing typical successful groundwater bore locations (after Allen, 1996).

Localised groundwater supplies may also be obtainable from fractures and regolith in the weathered profile in the basement rocks. Fracturing and weathering in rocks is highly differential and the degree will vary over short distances. This can result resulting in highly variable groundwater yields and sometimes in the drilling of dry wells. Geophysical maps such as Total Magnetic Intensity (TMI) as shown in Figure 13 may be used to help identify lineaments and shear zones. Bore yields in the weathered/fractured rock is the lowest at about 16 kL/day.

There appears to be a greater potential for groundwater supplies from palaeochannels and calcrete in the Musgrave Province where very high bore yields have been found. However the data is probably based on short term tests at the time of drilling and may not represent the long-term flow from aquifers. The thickness of the calcrete/sediment sequence is 30 m on average and some of these deposits extend over large areas (>100 km^2). Calcrete may display karstic features such as sinkholes (Allen, 1996) from which higher yields of groundwater may be sourced. Calcrete can have a wide variation in salinity (600 to 25,000 mg/L) depending on its location within the flow system, with those located in the lower reaches are likely to have higher salinity. Average bore yields in calcrete are the highest in the region at about 170 kL/day, however, yields of up to 250-1000 kL/day have been observed in some bores.

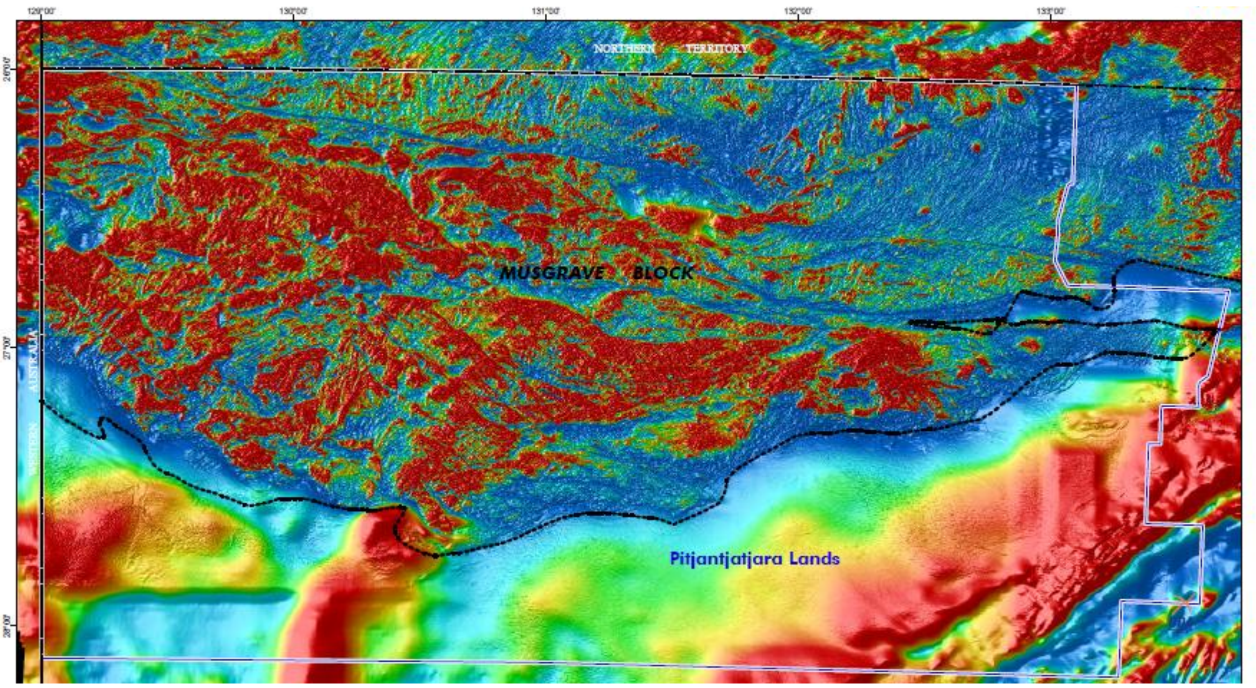

Figure 13: Total Magnetic Intensity (TMI) image of Musgrave Province (Gum and Conor, 2003).

Lewis et al. (2010) considered the palaeovalleys to be best targets for groundwater supply while recognising that only limited drilling has taken place. The average yield of wells in the palaeochannel sediments is about 100 kL/day with some bores having airlift yields of up to 600 kL/day. The groundwater salinity in palaeochannels is also high with an average of 4500 mg/L. However, most palaeochannel bores in the Musgrave Province have a salinity less than 3000 mg/L. Bore yields and salinity are both likely to increase downstream. However, Lewis et al. (2010) suggested that occurrence of fresh groundwater in some palaeovalleys may be due to enhanced local recharge from runoff across hard calcrete surfaces.

The sandstone and shale of the Officer Basin sediments in the southeastern margin of the study area offer limited groundwater potential in the fractured sandstone of the Ordovician Mt Chandler Sandstone. Bores at the Indulkana community have shown that they are capable of being pumped at higher rates. The groundwater salinity is mostly less than 2000 mg/L (Table 2).

The potential for large-scale groundwater supplies in the Musgrave Province has not been investigated on a regional scale, apart from low yielding fresh groundwater supplies for the aboriginal communities. So far there has been no study of the aquifer sustainable yields, however, sustainability of individual aboriginal community water supply wells have been assessed (Australian Groundwater Technologies, 2010). A detailed drilling and testing programme would be required for the establishment of well fields and obtaining large-scale groundwater supplies. It appears likely that the most reliable supplies can be obtained from palaeochannels and calcrete.

The estimated recharge to groundwater of <1 mm/yr equates to <60 ML/yr which is significantly lower that the current level of abstraction in the region. If this is the only major form of recharge in the area (i.e. there is little localised recharge with significantly higher rates than 1 mm/yr) then any large-scale groundwater abstraction will likely cause a depletion of the groundwater resource. Figure 14 and Figure 15 show the historical water level trends in the aboriginal communities bores in the Musgrave Province. Groundwater supply wells in Amata, Pukatja, Umuwa and Yunyarinyi communities all have declining water levels due to the abstraction being in excess of the sustainable yields. These bores are usually close to the Precambrian outcrops where the aquifer thickness and extent is likely to be low. However, a rise in the water level post 2001 is interpreted to be the direct result of higher than average rainfall of 700 mm in that year. The community bores with stable or rising water levels such as Indulkana and Pipalyatjara are located in the onlapping Officer Basin sediments and calcrete respectively, where higher aquifer yields are possible.

5.3 Climate change impacts on groundwater

According to the Bureau of Meteorology climate trend maps (http://www.bom.gov.au/cgi-bin/climate/change/trendmaps.cgi?map=rain&area=aus&season=0112&period=1970), the annual rainfall trend for 1970-2010 varies from a 5 mm/10 years increase in the west to 20 mm/10 years decrease in the eastern part of the Musgrave Province. The mean temperature trend during this period has increased from 0.15 to 0.2°C/10 years. This minor decline in the rainfall in the west appears to have had minimal effect on the groundwater levels as observed in selected observation bores in the area (Figure 16). However, some caution should be exercised as there is a lack of long term groundwater level monitoring bores in the area and most that exist are close to water supply bores and hence are affected by pumping. Barron et al. (2011) conducted a study of impacts of climate change on various aquifers in Australia. The Musgrave Province was considered a low priority area for the study and was not included in a more comprehensive assessment of the impact of climate change. The study, however, suggested that the fractured rock aquifer type, which is common in the Musgrave Province, is more sensitive to climate change due to the low storage.

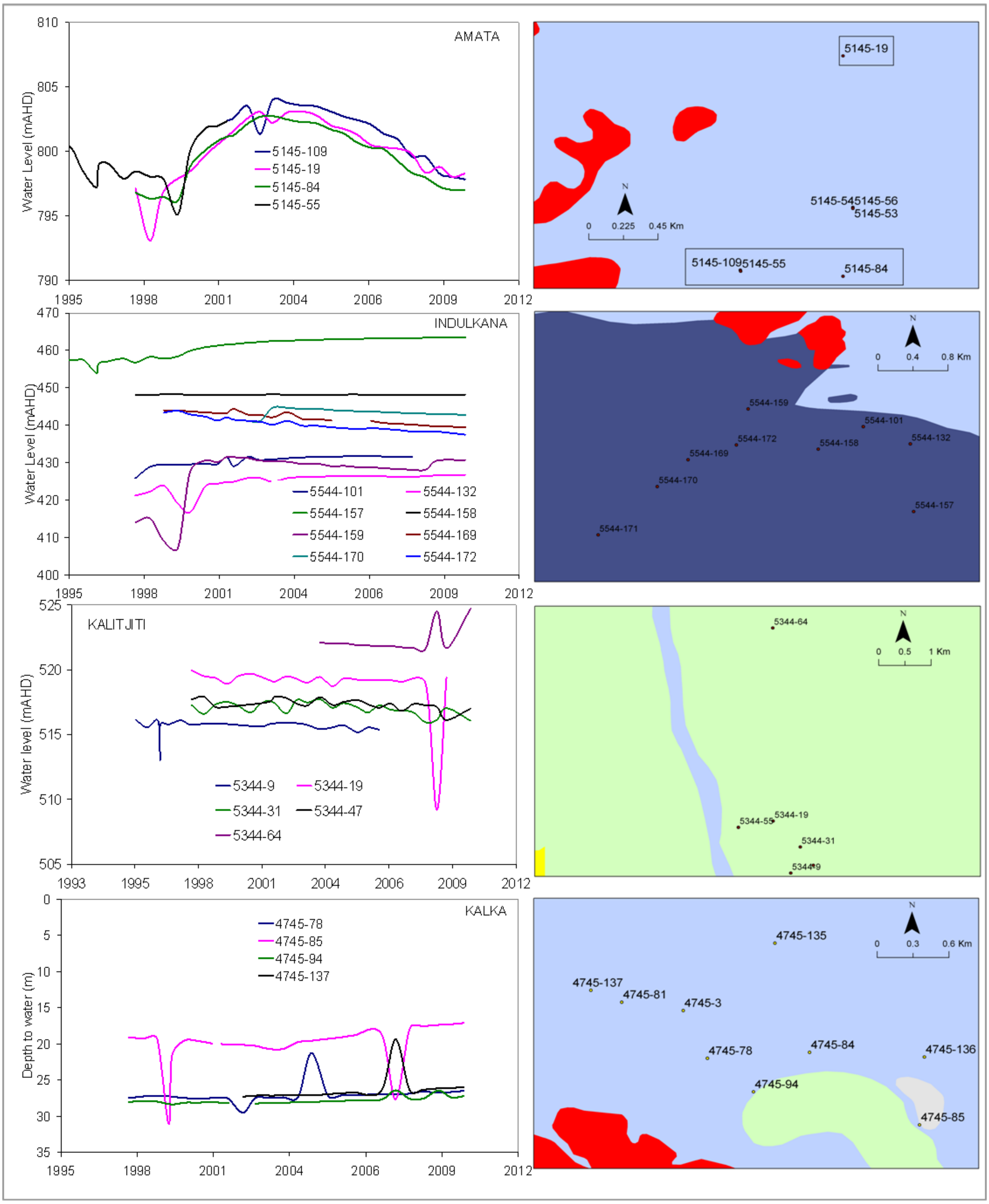

Figure 14: Water level trends in the aboriginal community bores - Amata, Indulkana, Kaltjiti and Kalka communities. The adjacent map shows the surface geology at the bores. The location of the community and the colour codes for the geology are shown in Figure 6.

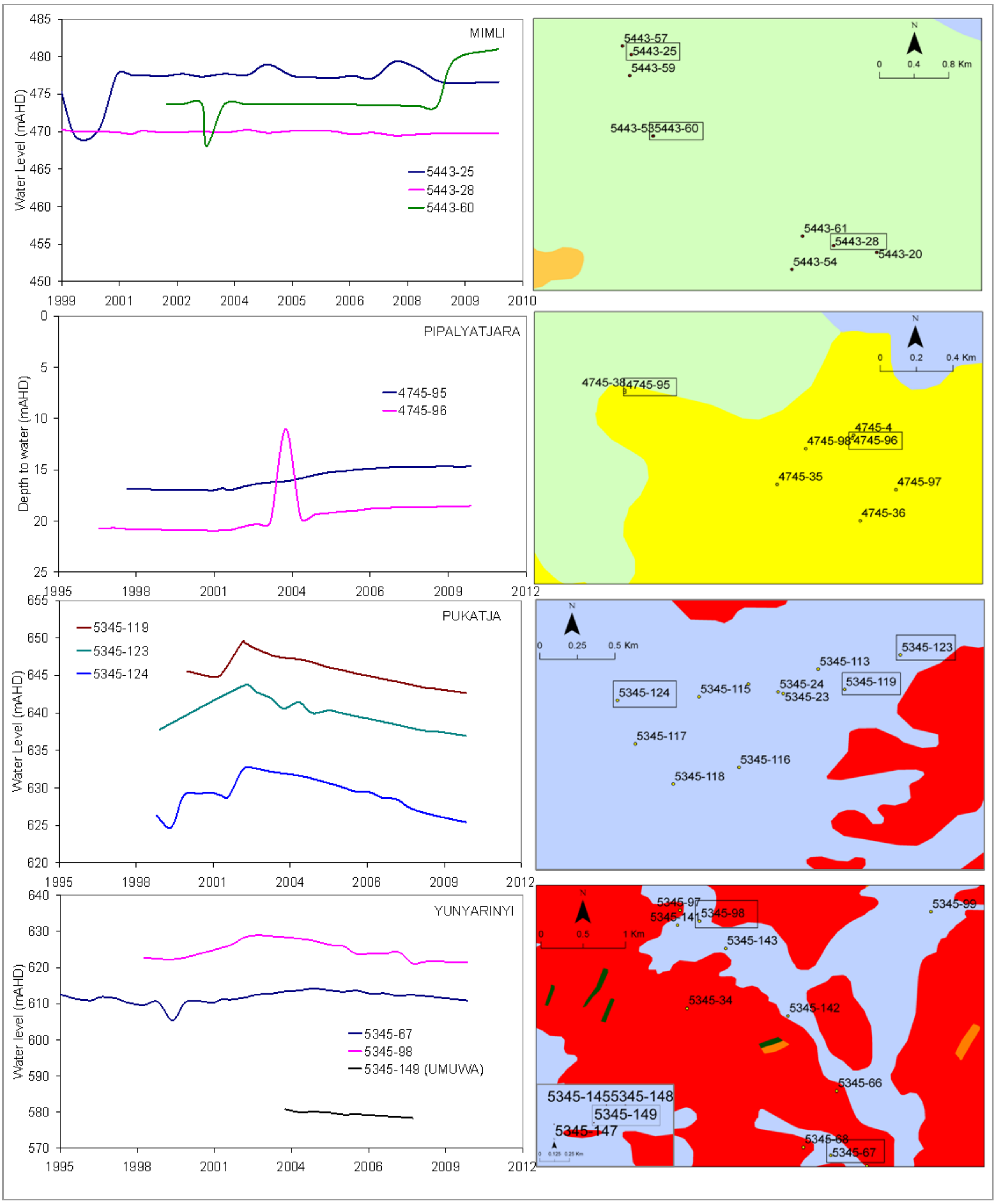

Figure 15: Water level trends in the aboriginal community bores - Mimli, Pipalyatjara, Pukatja, Yunyarinyi and Umuwa communities. The adjacent map shows the surface geology at the bores. The location of the community and the colour codes for the geology are shown in Figure 6.

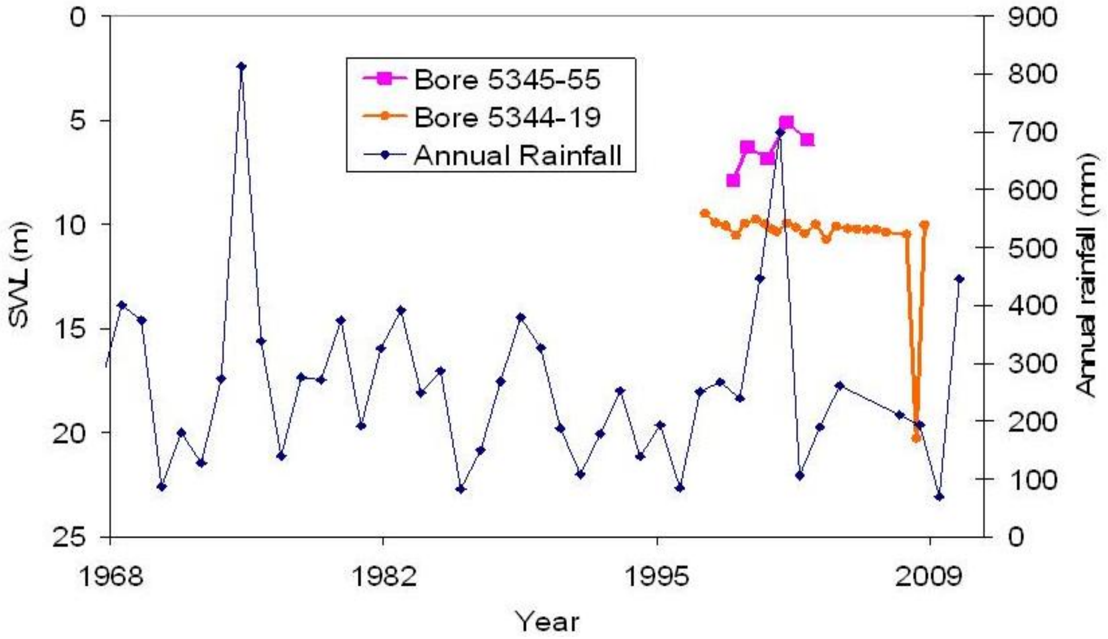

Figure 16: Hydrographs of selected bores in the Musgrave Province showing minimal effect of annual rainfall the static water level (meters below natural surface).

6 CONCLUSIONS

The Musgrave Province consists of Precambrian basement granitoids and gneisses that underlie aeolian, alluvial and fluvial sediments. Several Tertiary palaeochannels and calcrete deposits occur throughout the region. These sediments together with a fractured and weathered zone in the basement rocks contain limited groundwater resources of the region that are used for remote aboriginal communities and stock water supplies.

The Musgrave Province lies in a semi-arid zone with an unreliable rainfall. As a result of the low rainfall, the diffuse recharge to the groundwater is minimal (<1 mm/year). However, periodic episodes of higher than average rainfall provide occasional higher recharge to the aquifers and some extra localised recharge near ephemeral creeks and waterholes is likely.

There is very little data regarding watertable elevation, and there is no information on aquifer permeability that would enable estimation of groundwater throughflow. Based on limited data availability, a synoptic watertable map has been prepared for the eastern part of the region which shows that the groundwater flow in the southeasterly direction is likely under a hydraulic gradient of 0.0015.

The calcretes and palaeovalley sands have potential for supply of moderate volumes of potable groundwater; however, there appears to be only a limited scope for obtaining large-scale water supplies in the region without depleting the resource. Water levels in groundwater supply bores are steadily declining in some areas indicating a low level of replenishment compared to the rate of abstraction, except in some communities such as Indulkana where there are prospects of obtaining higher yields from the Mt Chandler Sandstone of the Officer Basin. However, these conclusions are based on very limited available data and additional investigations are required to better map the overburden thickness, depth to water and estimates of hydraulic properties to allow an improved assessment of the groundwater occurrence and yields in the Musgrave Province.

7 RECOMMENDATIONS

This desk top evaluation of the hydrogeology of the Musgrave Province has identified data gaps that are important for an improved understanding of the groundwater resources of Musgrave Province. A two-stage investigation and assessment programme is recommended involving collection, interpretation and analysis of data. Specific recommendations are:

Stage 1: Groundwater investigation

1. Survey of all bores in the study area to obtain top of casing and ground elevations, bore depths, screened intervals, SWL and water samples for salinity and other water quality parameters.
2. Slug injection/recovery tests in selected bores for estimation of hydraulic conductivities.
3. Borehole geophysical surveys (e.g. nuclear magnetic resonance logs) in selected bores for the estimation of porosity and permeability.
4. Ground geophysical surveys to produce maps of regolith thickness, preferably tied in with exploratory drilling to better define the aquifer character.
5. Watertable contour maps for the entire Musgrave Province to identify different flow systems and quantify groundwater flow.

Stage 2: Groundwater resource assessment

1. Test-pumping and monitoring of selected bores in calcrete, palaeochannels and the Officer Basin sediments on the southeastern margin to obtain estimates of transmissivity, hydraulic conductivity, specific yield, storage coefficients and sustainable yields. Consider drilling of new bores if there is a lack of suitable existing bores.
2. Local-scale numerical groundwater models to test various scenarios of groundwater abstraction and its impact on the surrounding groundwater levels and quality.

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GLOSSARY

Abstraction	The withdrawal of water from any water resource
AHD	Australian Height Datum; equivalent to: Mean Sea Level (MSL) + 0.026 m; Low Water Mark Fremantle (LWMF) + 0.756 m
Allocation Limit	The volume of water set aside for annual licensed use
Alluvium	Unconsolidated sediments transported by streams and rivers and deposited
MGA	Map Grid of Australia
Anticline	Sedimentary strata folded in the usually of inverted U-shape
Anoxic	An environment that is depleted of dissolved oxygen
Aquifer	A geological formation or group of formations able to receive, store and transmit significant quantities of water
Unconfined	A permeable bed only partially filled with water and overlying a relatively impermeable layer. Its upper boundary is formed by a free watertable or phreatic level under atmospheric pressure
Confined	A permeable bed saturated with water and lying between an upper and a lower confining layer of low permeability, the hydraulic head being higher than the upper surface of the aquifer
Semi-confined	A semi-confined or a leaky aquifer that is saturated and bounded above by a semi-permeable layer and below by a layer that is either impermeable or semi-permeable
Semi-unconfined	Intermediate between semi-confined and unconfined, when the upper semi-permeable layer easily transmits water
Archaean	Period containing the oldest rocks of the Earth's crust – older than 2.4 billion years
Baseflow	Portion of river and stream flow coming from groundwater discharge
Basement	Competent rock formations beneath which sedimentary rocks are not found
Bore	A narrow, normally vertical hole drilled into a geological formation to monitor or withdraw groundwater from an aquifer. see <u>Well</u>
Colluvium	Material transported by gravity downhill of slopes
Confining bed	Sedimentary bed of very low hydraulic conductivity
Conformably	Sediments deposited in a continuous sequence without a break
Cretaceous	Final period of Mesozoic era; 65-144 million years ago
Dewatering	Short-term abstraction of groundwater to lower the water table and permit the excavation of 'dry' sediment
Ecologically sustainable yield	The amount of water that can be abstracted over time from a water resource while maintaining the ecological values (including assets, functions and processes)
Ecological water requirement	The water regime needed to maintain the ecological values (including assets, functions and processes) of water dependent ecosystems at a low level of risk.
Environmental water provision	The water regimes that are provided as a result of the water allocation decision-making process taking into account ecological, social, cultural and economic impacts. They may meet in part or in full the ecological water requirements

Evapotranspiration	A collective term for evaporation and transpiration. It includes water evaporated from the soil surface and water transpired by plants
Fault	A fracture in rocks or sediments along which there has been an observable displacement
Flux	Flow
Formation	A group of rocks or sediments which have certain characteristics in common, were deposited about the same geological period, and which constitute a convenient unit for description
Groundwater dependent ecosystem	An ecosystem that is dependent on groundwater for its existence and health
Hydraulic	Pertaining to water motion
Conductivity	The flow through a unit cross-sectional area of an aquifer under a unit hydraulic gradient
Gradient	The rate of change of total head per unit distance of flow at a given point and in a given direction
Head	The height of the free surface of a body of water above a given subsurface point
Interburden	Material that lies between two or more bedded zone such as coal seams
Lacustrine	Pertaining to, produced by, or formed in a lake
Leach	Remove soluble matter by percolation of water
MGA	Map Grid of Australia
Permian	An era of geological time; 225–280 years ago
Petrographic	An analysis, description and classification of rocks such as by means of a microscope
Porosity	The ratio of the volume of void spaces, to the total volume of a rock matrix
Potentiometric surface	An imaginary surface representing the total head of groundwater and defined by the level to which water will rise in a bore
Quaternary	Relating to the most recent period in the Cainozoic era, from 2 million years to present
Salinity	A measure of the concentration of total dissolved solids in water 0–500 mg/L, fresh 500–1500 mg/L, fresh to marginal 1500–3000 mg/L, brackish >3000 mg/L, saline
Scarp	A line of cliffs (steep slopes) produced by faulting or by erosion
Specific yield	The volume of water that an unconfined aquifer releases from storage per unit surface area of the aquifer per unit decline in the watertable
Storage coefficient	The volume of water that a confined aquifer releases from storage, per unit surface area of the aquifer, per unit decline in the component of hydraulic head normal to that surface
Sustainable yield	The level of water extraction from a particular system that, if exceeded, would compromise key environmental assets, or ecosystem functions and the productive base of resource

Syncline	A U-shaped fold in sedimentary strata
Tectonic	Pertaining to forces that produce structures or features in rocks
Tertiary	The first period of the Cainozoic era; 2–65 million years ago
Transmissivity	The rate at which water is transmitted through a unit width of an aquifer under a unit hydraulic gradient
Transpiration	The loss of water vapour from a plant, mainly through the leaves
Watertable	The surface of a body of unconfined groundwater at which the pressure is equal to that of the atmosphere
Well	An opening in the ground made or used to obtain access to underground water. This includes soaks, wells, bores and excavations