Pedirka Basin numerical groundwater model 2014

DEWNR Technical report 2015/04

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

Funding for these projects has been provided by the Australian Government through the Bioregional Assessment Programme.

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Foreword

The Department of Environment, Water and Natural Resources (DEWNR) is responsible for the management of the State's natural resources, ranging from policy leadership to on-ground delivery in consultation with government, industry and communities.

High-quality science and effective monitoring provides the foundation for the successful management of our environment and natural resources. This is achieved through undertaking appropriate research, investigations, assessments, monitoring and evaluation.

DEWNR's strong partnerships with educational and research institutions, industries, government agencies, Natural Resources Management Boards and the community ensures that there is continual capacity building across the sector and that the best skills and expertise are used to inform decision making.

Sandy Pitcher
CHIEF EXECUTIVE
DEPARTMENT OF ENVIRONMENT, WATER AND NATURAL RESOURCES

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Representatives from various disciplines formed a reference group, with emphasis on providing data, information, knowledge and providing observations and advice regarding purpose, methodology and approach of the modelling. Members of the reference group include:

- Volmer Berens [Department of Environment, Water and Natural Resources (DEWNR)]
- Wei Yan (DEWNR)
- Peter Baker (OWS)
- Kriton Glenn (Geoscience Australia)
- John Wischusen (Department of Land Resource Management, Northern Territory Government)
- Andy Love (Flinders University)
- Russel Crosbie (CSIRO)
- Chris Turnage (CSIRO)

The following DEWNR staff are acknowledged for providing hydrogeological data and contributing toward development of the conceptual model:

- Daniel Wohling
- Lloyd Sampson
- Simon Fulton
- Mark Keppel

Graham Green (DEWNR) provided understanding of long-term trends in climate, and likely impact on diffuse recharge to the Pedirka Basin.

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Summary

In recognition of the coal mining development potential, data scarcity and water resource significance, the Australian Government through the Department of the Environment provided funding to the Government of South Australia, in partnership with the Northern Territory Government, to undertake groundwater assessments of the Arckaringa Basin and Pedirka Basin. Stage One of the project has been completed, and Stage Two is currently ongoing. Stage Two involves field studies to address key data and knowledge gaps identified in Stage One. Incorporated within the Stage Two scope of work is the development of a separate numerical groundwater model for both the Arckaringa Basin and Pedirka Basin. This report describes the development of a numerical groundwater model for the Pedirka Basin.

The purpose of the modelling exercise was to improve our understanding of the groundwater system by testing our current conceptual model, providing an estimation of regional-scale water balance, conducting sensitivity testing and defining data and knowledge gaps. A regional-scale MODFLOW model has been developed for the Pedirka Basin using available data and current information, and is defined as a low confidence-level model (Class 1, Barnett et al., 2012) for any associated predictions based on limited data availability and level of calibration achievable. A transient groundwater model has been developed that simulates the main processes occurring in the basin in the past, present and into the future, and therefore includes simulation of the current condition.

A model confirmation process was conducted to be consistent with the system behaviour, including water level as measured and inferred flow directions. The transient-model results indicate that water levels in the basin are currently declining, discharge is greater than recharge and the system is not currently in equilibrium. The model validates the current conceptual understanding of the basin, indicating that modern-day recharge to the basin may occur via river recharge and lateral inflow through the GAB aquifer, and that discharge is mostly via lateral outflow through the GAB aquifer.

Due to the complicated geological structure of the basin, a number of simplifications and assumptions are made to improve numerical stability. Model limitations are closely associated with assumptions, simplifications and data uncertainties. It is recommended that numerical stability is investigated in future works, however the model is still considered fit for purpose for this project.

Sensitivity tests were undertaken to assess changes in aquifer hydraulic conductivity, aquifer storage and diffuse recharge. The tests gained better understanding of how the system responds to variation in parameters and stresses. The results show that changes to the hydraulic conductivity of the GAB aquifer are most sensitive, and that storage changes affect the time taken for the system to reach equilibrium.

A hypothetical mine dewatering scenario was simulated, indicating the estimated impact of drawdown is regionally widespread, and is related to the horizontal and vertical connectivity between the modelled aquifers. The test indicates that drawdown may occur in the GAB aquifer near Dalhousie Springs, but the aquifer remains artesian over the period of testing (50 years). More robust sensitivity testing to support the model is recommended for future works.

The outcome of the modelling exercise is a compiled existing-data, information and knowledge package that will be useful for future modelling and investigation projects. It is recommended that the conceptual model be refined and the numerical model upgraded as more data and information are obtained. The modelling exercise proved valuable in identifying key knowledge and data gaps, and it is hoped that this discovery may direct planning of future field investigations or activities. Key recommendations for future modelling are provided in Section 7.

1 Introduction

In 2012, the Australian Government established an Independent Expert Scientific Committee (IESC) on Coal Seam Gas (CSG) and Large Coal Mining (LCM) developments to provide independent, expert scientific advice on the future impact these activities may have on water resources. The IESC is a statutory body under the *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act) which provides scientific advice to Australian governments on the water-related impacts of coal seam gas and large coal mining development proposals. Under the EPBC Act, the IESC has several legislative functions to:

- Provide scientific advice to the Commonwealth Environment Minister and relevant state ministers on the water-related impacts of proposed coal seam gas or large coal mining developments
- Provide scientific advice to the Commonwealth Environment Minister on:
  - Bioregional assessments being undertaken by the Australian Government, and
  - Research priorities and projects commissioned by the Commonwealth Environment Minister
- Publish and disseminate scientific information about the impacts of coal seam gas and large coal mining activities on water resources.

The Bioregional Assessment Programme is a transparent and accessible programme of baseline assessments that increase the available science for decision making associated on potential water-related impacts of coal seam gas and large coal mining developments. A bioregional assessment is a scientific analysis of the ecology, hydrology, geology and hydrogeology of a bioregion with explicit assessment of the potential direct, indirect and cumulative impacts of coal seam gas and large coal mining development on water resources. This Programme draws on the best available scientific information and knowledge from many sources, including government, industry and regional communities, to produce bioregional assessments that are independent, scientifically robust, and relevant and meaningful at a regional scale. For more information on bioregional assessments, visit <http://www.bioregionalassessments.gov.au>.

The South Australian Department of Environment, Water and Natural Resources (DEWNR), was commissioned by the Australian Government through the Department of the Environment to collate and ground-truth baseline groundwater, surface water and ecology information to inform the Bioregional Assessment Programme in the Lake Eyre Basin. The Lake Eyre Basin (LEB) bioregion (Figure 1.1) has been identified as one of six priority areas for a bioregional assessment across Australia. This report is part of a series of studies forming part of the Arckaringa Basin and Pedirka Basin Groundwater Assessment project. The Arckaringa Basin and Pedirka Basin Groundwater Assessment project is one of three water knowledge projects undertaken by DEWNR in the western Lake Eyre Basin bioregion, including the:

- Lake Eyre Basin Rivers Monitoring project
- Arckaringa Basin and Pedirka Basin Groundwater Assessment project
- Lake Eyre Basin Springs project.

This reports documents the development of a numerical groundwater model for the Pedirka Basin and forms a key component of the Arckaringa Basin and Pedirka Basin Groundwater Assessment. Given that the Pedirka Basin extends across both South Australia and the Northern Territory, DEWNR sub-contracted relevant Northern Territory agencies to contribute to this project.

1.1 Objectives of the modelling exercise

The development of a groundwater model for the Pedirka Basin will promote an understanding of the hydrogeological system by testing the validity of the current conceptual model through sensitivity tests and providing an estimate of a regional scale water balance.

The modelling exercise is valuable in verifying key knowledge and data gaps, which may direct planning of future field investigations or activities. The outcome of the modelling exercise is a compiled data, information and knowledge package that can be considered for future modelling/investigation projects.

Based on project scope, timing and data availability constraints, the model will not incorporate the small-scale level of detail that is required to undertake risk assessment scenario modelling. However, the model can form a basis for potential improvements and refinements to suit future purposes.

The design of a Pedirka Basin groundwater model is constrained by data availability and knowledge gaps. According to the Australian Groundwater Modelling Guidelines (Barnett et al., 2012), the groundwater model developed for Pedirka Basin is considered as a regional scale, elementary model of low complexity, defined as Class 1.

1.2 Review of existing models

Based on a search of current publications, no regional scale numerical models have been previously developed for the Pedirka Basin to simulate Permian aquifers.

GABtran is a regional model that simulates the entire Great Artesian Basin (GAB) aquifer (Welsh, 2006) and is regarded as the contemporary model for the GAB. GABtran is a single layer model representing the main GAB aquifer, with interaction between overlying and underlying aquifers represented as vertical leakage, however it does not simulate interaction with older and deeper aquifers that can exist in underlying basins, such as the Permian aquifers of the Pedirka Basin.

The GABtran model predicts that the groundwater system is not in hydraulic equilibrium; that discharge exceeds recharge and groundwater levels will continue to fall until this is reversed. GABtran has recently been used to estimate the impact of climate and groundwater development on groundwater levels in the GAB, as part of the Great Artesian Basin Water Resource Assessment (Welsh et al., 2012).

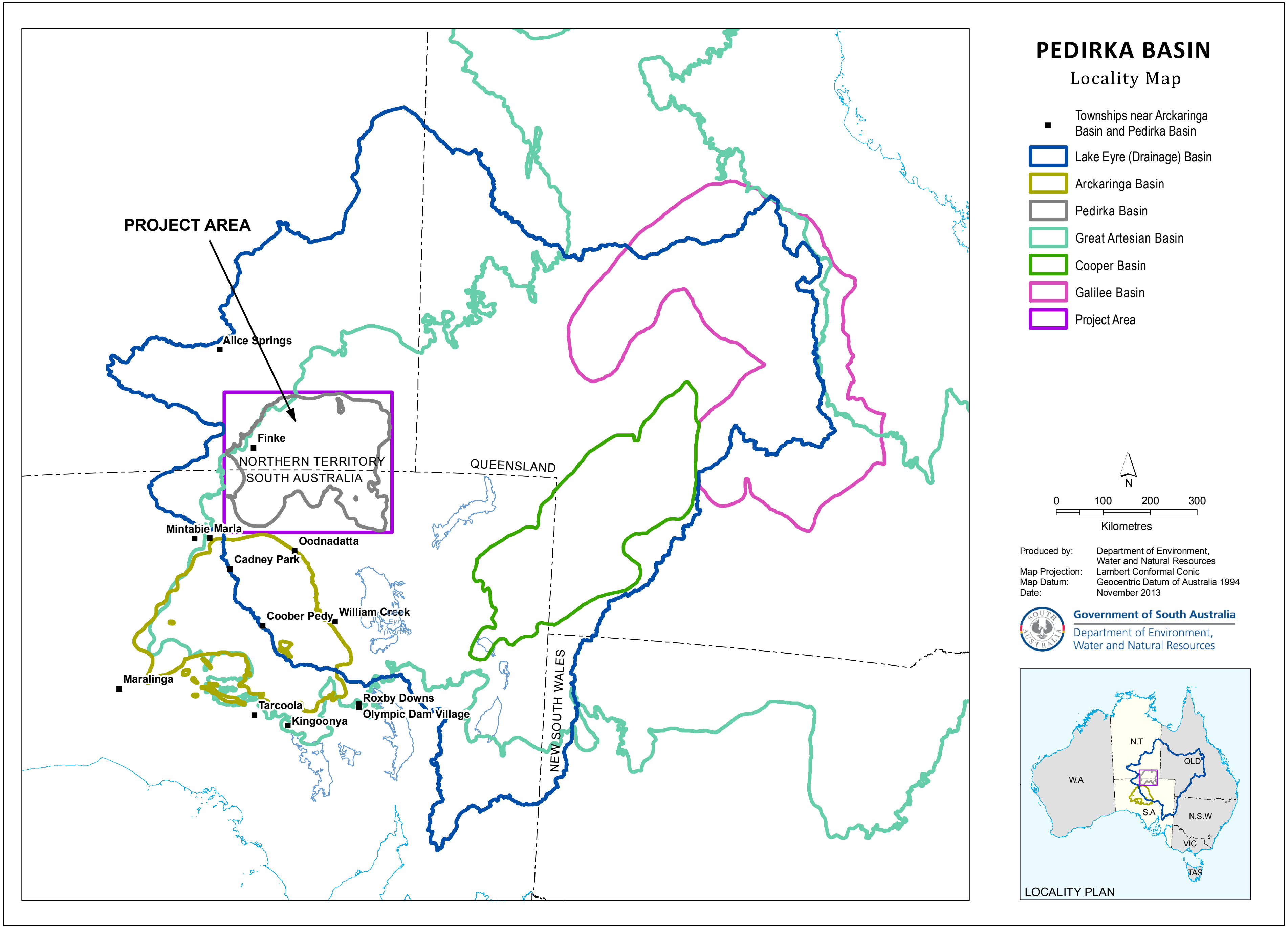

Figure 1.1: Pedirka Basin Location Map

2 Hydrogeology and hydrology of the Pedirka Basin

The report developed at the conclusion of Stage One summarises and evaluates available data and current conceptual understanding for the Pedirka Basin (Wohling et al., 2013). This section summarises key aspects of the hydrogeology and hydrology and includes new information gathered since the completion of Stage One for the modelling exercise.

2.1 Location and topography

The Pedirka Basin is centred on the South Australia–Northern Territory border, approximately 860 km north to north-west of Adelaide and approximately 160 km south of Alice Springs. The spatial extent of the Pedirka Basin covers an area of approximately 60 000 km^2. Figure 1.1 shows the location of the Pedirka Basin in relation to Lake Eyre (Drainage) Basin, Great Artesian Basin and other basins. Figure 2.1 shows the topography and key hydrological features, including Finke River, Goyder Creek and Dalhousie Springs.

The topography of the project area (Pedirka Basin) is largely flat-lying or controlled by dune field development. Longitudinal dunes of the Simpson Desert can extend for several hundred kilometres and attain heights of up to 40 m (Ambrose cited in Wohling et al., 2013). Elevation ranges between 0 m AHD and 450 m AHD, with a mean elevation of approximately 144 m AHD.

2.2 Climate

The climate of central Australia has been described by Allan (1990) and McMahon et al. (2005) as arid; while Stern et al. (2000) describes the region as 'desert' (Wohling et al., 2013). Average maximum peak-summer monthly temperatures range between 36.1 °C and 39.5 °C, although daily maximums are regularly above 40 °C. In contrast, the minimum peak-winter monthly temperatures range from 4.9 °C and 6.4 °C, although daily minimums may reach below 0 °C.

Published rates of pan-evaporation range between 2500 mm/y and 3000 mm/y (Wohling et al., 2013). Rainfall in the Pedirka Basin is reliant on northern-derived monsoonal precipitation. A distinctive rainfall gradient occurs across the basin, with average annual rainfall generally decreasing from approximately 200 mm/y in the west–north-west to 150 mm/y in the east–south-east (Figure 2.2).

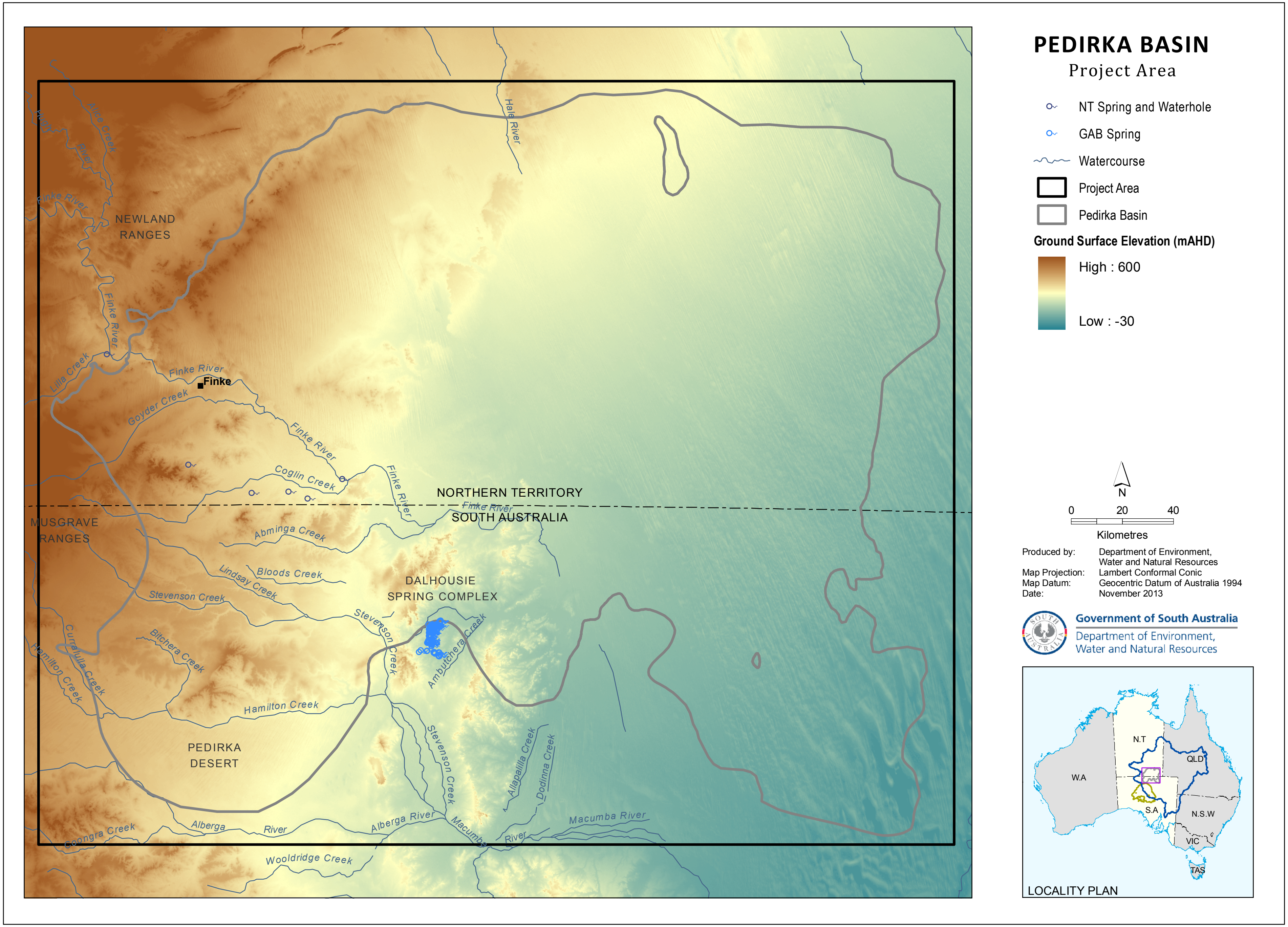

Figure 2.1: Pedirka Basin project area

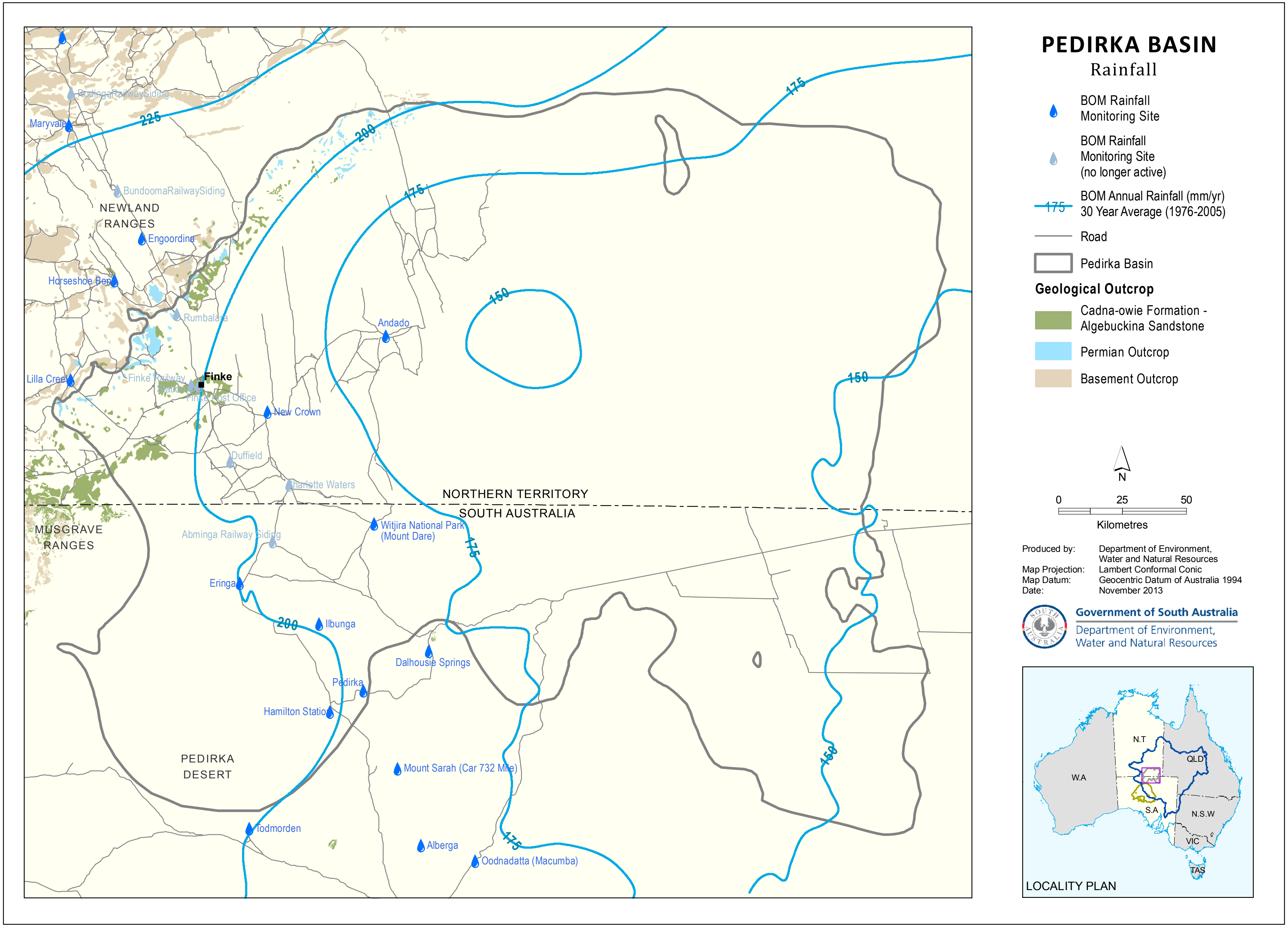

Figure 2.2: Pedirka Basin average annual rainfall

2.3 Regional geology and hydrogeology

The Pedirka Basin is a sedimentary basin comprising mainly Early to Late Permian sediments and coal sequences. The basin unconformably overlies the Early-Palaeozoic Amadeus and Warburton Basins and Proterozoic basement rocks. The Pedirka Basin unconformably underlies the Mesozoic Eromanga Basin, synonymous with the Great Artesian Basin, and the Triassic Simpson Basin in the eastern extent. Tertiary sediments of the Lake Eyre (geological) Basin, Hamilton sub-basin and paleochannels overlie the GAB. The spatial relationship between the Pedirka Basin and other geological basins is given in Figure 2.3.

There are two major recognised hydrogeological formations within the Pedirka Basin: the Purni Formation and the underlying Crown Point Formation. The Crown Point Formation is an aquifer along the western margin of the basin, however little is known in the central and deeper parts of the basin. Much of the Pedirka Basin occurs subsurface at depths greater than 400 m, although outcrop of Crown Point Formation is known to occur along the western margin of the basin (Wohling et al., 2013).

The hydrogeological nature of the basin is influenced by geological structures (faults and folds) within and surrounding the basin (Figure 2.4). The basin is bound to the south-west by the Musgrave Ranges. The northern boundary is defined by the Arunta Block and a complex fault block called the Hale River High, the location of which is controlled by the Pellinor Fault Zone (Wohling et al., 2013). The Pedirka Basin is separated from the Arckaringa Basin to the south and the similarly-aged Cooper Basin to the east by the basement highs of the Bitchera, Muloorina and Birdsville Track Ridges. It has been postulated that the Pedirka Basin was once connected to the other Permo-Carboniferous basins across these basement highs but was subsequently isolated by the erosion of Permian sediments (Hibburt and Gravestock cited in Wohling et al., 2013).

A major north-west geological structural feature called the Dalhousie-McDills Ridge dissects the Pedirka Basin into eastern (Madigan and Poolowanna Troughs) and western (Eringa Trough) portions. The basin reaches a maximum thickness of up to 1525 m within the Eringa Trough. The Poolowanna Trough occupies the far eastern portion of the basin and is separated from the Madigan Trough by the Colson Shelf, upon which thickness of Permian sediments is approximately 135 m.

Table 2-1 provides a summary of the hydrogeological formations encountered with depth within the Pedirka Basin study extent (from Keppel et al., 2013 and Wohling et al., 2013). A detailed description of the major geological and hydrogeological formations in the Pedirka Basin are presented in Section 2.4.

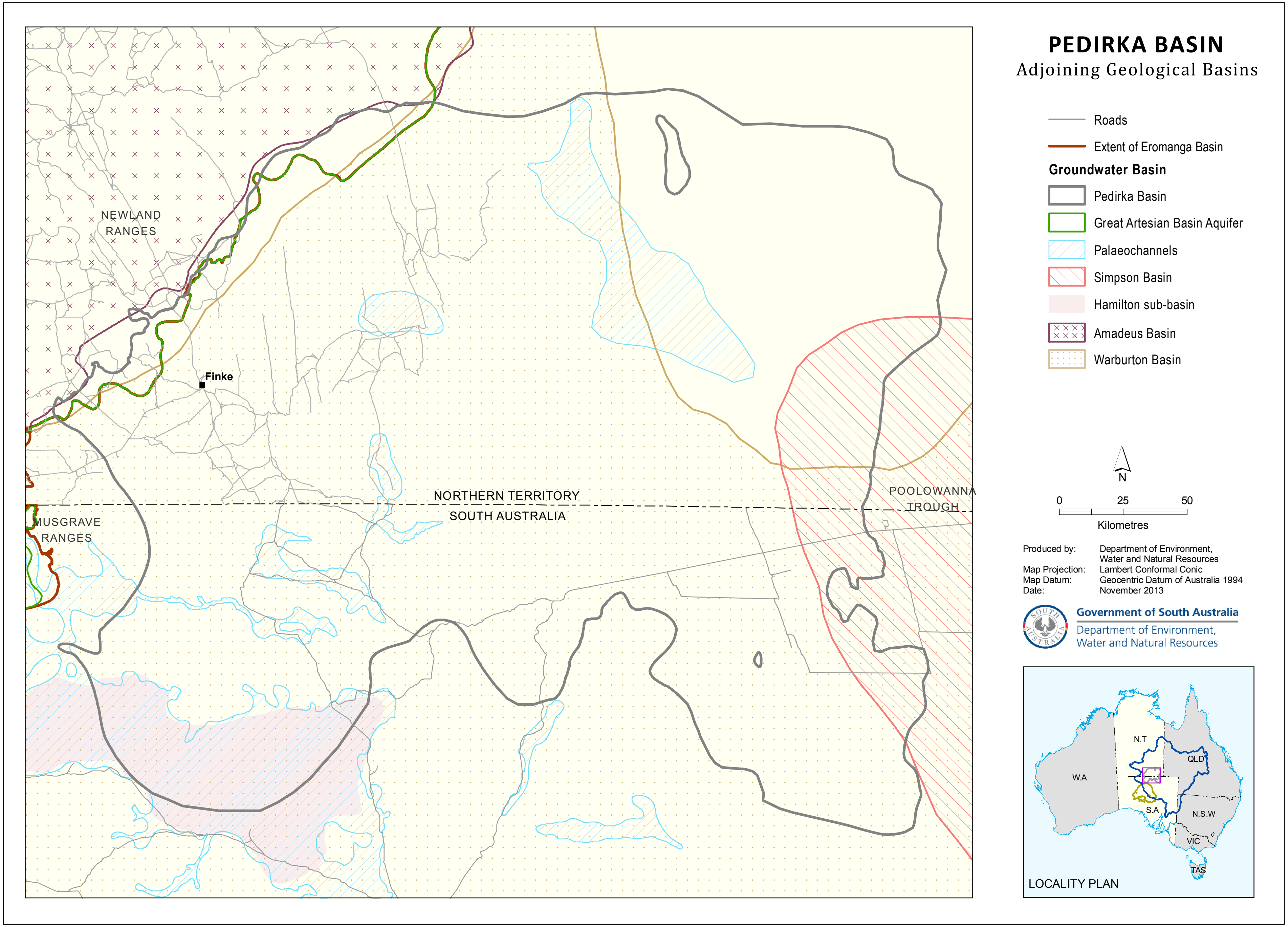

Figure 2.3: Pedirka Basin adjoining geological basins

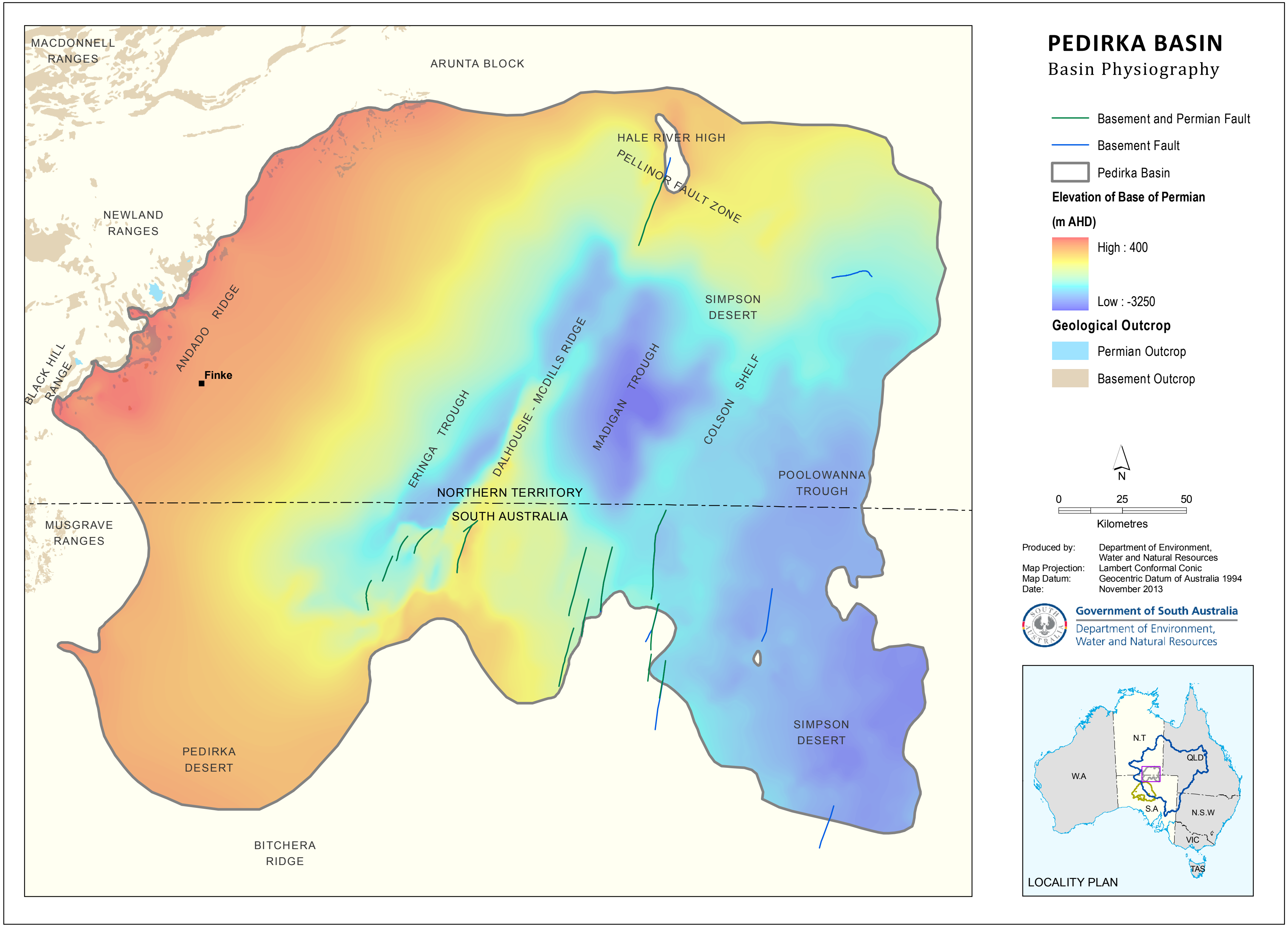

Figure 2.4: Pedirka Basin physiography

Table 2-1 Description of geological and hydrogeological formations within the study extent

Geological basin	Hydro-stratigraphy	Geological unit(s)	Era	Depositional environment	Description of lithology	Hydrogeological characteristics
-	Cainozoic	-	Tertiary to Quaternary	Fluvial and lacustrine	-	Discrete aquifers
Great Artesian Basin	Rolling Downs Group	Bulldog Shale Rumbalara Shale Oodnadatta Formation lateral equivalents	Cretaceous to Jurassic	Low energy marine	Marine clays, silts and shales	Aquitard
Great Artesian Basin	J aquifer	Cadna-owie Formation Algebuckina Sandstone DeSouza Sandstone lateral equivalents	Mid-Cretaceous to Jurassic	Marine transitional and terrestrial	Fine to coarse grained sandstone and siltstone	Aquifer
Simpson Basin	Triassic	Walkandi Formation Peera Peera Formation	Triassic	Fluvial-floodplain-lacustrine	Shale, siltstone, minor sandstone and coal	Potential aquitard (poorly understood)
Pedirka Basin	-	Purni Formation	Permian (298.9 – 254.1 Ma)	Fluvial and paludal	Interbedded sands, silts and clays with coal beds within the upper paludal sequences	Potential aquifers and Aquitards within the one formation; poorly understood
Pedirka Basin	-	Crown Point Formation	Permian (298.9 – 295.0 Ma)	Glacio-fluvial and glacio-lucastrine	Sands and shales (diamictite)	Potential aquifer
Warburton Basin	Basement	Finke Group	Cambrian to Devonian	Epeiric to marine	Sedimentary basin; poorly understood	Poorly understood
Amadeus Basin	Basement	Hermannsburg Sandstone Mereenie Sandstone Pacoota Sandstone	Neoproterozoic to early-Carboniferous	Marine to fluvial	Marine siliciclastic and carbonate and sandstone	Poorly understood
-	Basement	-	Proterozoic and Archaean	-	Crystalline and igneous	Poorly understood

2.4 Geology and hydrogeology within the Pedirka Basin project area

In the project area, the following basins and their hydrogeological units were considered in the modelling project:

- Great Artesian Basin (Rolling Downs Group and J Aquifer)
- Simpson Basin (Triassic Formation)
- Pedirka Basin (Purni Formation and Crown Point Formation)
- Basement.

Basin cross-sections which demonstrate the major hydrogeological units are shown in Figure 2.5.

2.4.1 GAB formation

The Great Artesian Basin (GAB) encompasses the Eromanga, Surat and Carpentaria Basins, however in South Australia and the southern Northern Territory it is synonymous with the Eromanga Basin. Geologically, the GAB formation describes a terrestrial to marine Cretaceous–Jurassic hydrogeological super basin that covers much of eastern and central Australia. GAB sediments unconformably overly the majority of the Pedirka Basin. In the Pedirka Basin area, the GAB Formation is formed by two main hydrogeological units - the Rolling Downs Group (aquitard) and J Aquifer.

2.4.1.1 Rolling Downs Group

The Rolling Downs Group includes layers such as the Bulldog Shale, Rumbalara Shale, Oodnadatta Formation and lateral equivalents. Little information is available regarding the hydraulic properties of the Rolling Downs Group. Literature review estimates of vertical hydraulic conductivity range between 3.46 x 10^{-9} m/d and 8.64 x 10^{-9} m/d (Keppel et al., 2013). Such low vertical hydraulic conductivity indicates that the Rolling Downs Group should act as an aquitard in the system. Vertical discharge through the Rolling Downs Group may be higher where preferential flow paths occur along fractures and faults (Love et al., 2013b).

2.4.1.2 J Aquifer

The J aquifer incorporates the Cadna-owie Formation, Algebuckina Sandstone, De Souza Sandstone and lateral equivalents. Generally it is described as a sandstone aquifer.

The hydraulic conductivity of the J aquifer along the western margin of the GAB, from previously published literature, ranges from a lower value of between 0.1 m/d and 1.6 m/d to a higher value of between 7 m/d and 20 m/d (Keppel et al., 2013). Storage coefficient ranges between 7 x 10^{-6} to 7 x 10^{-3} for the whole basin, with a mean value of 2.5 x 10^{-4} (Keppel et al., 2013).

A recent aquifer test undertaken along the Finke River recharge zone along the western margin of the Pedirka Basin suggests that the hydraulic conductivity of the J aquifer is higher locally along the Finke River than regionally.

A potentiometric surface for the J aquifer is given in Figure 2.6 (Keppel et al., 2013). Inferred direction of regional groundwater flow is from the north and the north-west along the margin of the Eromanga Basin toward the south-east. The J aquifer is unsaturated along the north-western extent of the basin. There are limited measurements available for the J aquifer within the eastern and south-eastern portions of the Pedirka Basin.

2.4.2 Simpson Basin Triassic Formation

There are two recognised Triassic formations within the Simpson Basin: the Peera Peera Formation and Walkandi Formation. The Walkandi Formation is largely restricted in extent to the Poolowanna Trough region at the centre of the Pedirka Basin. The sandstone interbeds of the Walkandi Formation are fine grained with low porosity and permeability (Goldstein cited in Wohling et al., 2013), although reservoir quality sands have been identified through log analysis (Questa cited in Wohling et al., 2013). The Walkandi Formation could provide a tight, potential seal to the underlying Permian where present (PIRSA, 2010). There are currently no reliable estimates of hydraulic conductivity properties for the Triassic sediments within the study area, but on the basis of lithology it is postulated that the Triassic may limit the vertical connectivity between the Permian aquifer and the J aquifer.

The thickness and extent of Triassic has been recently mapped using seismic and drilling data (Figure 2.7). Triassic sediments reach a maximum thickness of 340 m east of the Colson Shelf. There is a thin deposit of Triassic sediments within the Eringa Trough of less than 40 m. Triassic sediments are absent west of the Eringa Trough.

2.4.3 Pedirka Basin Permian Aquifers

There are two Permian formations within the Pedirka Basin that are defined as the Crown Point Formation and overlying Purni Formation. At present it is unclear whether the Purni Formation and Crown Point Formation behaves regionally as a single aquifer or whether multiple aquifers and aquitards exist within these formations. The Stage 2 field work program, which includes drilling and aquifer testing, will improve understanding of the hydrogeological characteristics of the Purni Formation and Crown Point Formation. Currently there are limited estimates of aquifer parameters (transmissivity, storage coefficients) for either the Purni Formation or Crown Point Formation, hence no estimate of groundwater flow rates are provided.

Sections 2.4.3.1 and 2.4.3.2 provide concise descriptions of the Purni Formation and Crown Point Formation. More detailed descriptions of these formations can be found in Wohling et al (2013). In the absence of additional information, the Purni Formation and Crown Point Formation will be regarded as separate aquifers and will be collectively referred to as the Permian aquifers.

2.4.3.1 PURNI FORMATION

The Purni Formation is comprised of sediments deposited during the Permian age and disconformably underlies Jurassic sediments of the Great Artesian Basin (or Triassic sediments, where present) and overlies the Crown Point Formation. The Purni Formation consists of fluvial and paludal interbedded sands, silts and clays, as well as coal beds within the paludal sequences.

At the time of writing this report, no aquifer tests have been undertaken to estimate the hydraulic parameters of the Purni Formation. Hydraulic conductivities have been derived from permeability measurements which are summarised below.

Table 2-2 Purni Formation porosity and permeability values (from Wohling at al., 2013)

Well name	Reference	Porosity (%)	Permeability (mD)	Derived hydraulic conductivity (m/d)*
Etingimbra	Osborne and Edwards (1990)	31–32		
Colson	Beach Petroleum (1979)	13–16		
Hale River No 1	Amerada Petroleum (1966)	15–22 (25)**	632 (Kv)# 2529 (Kh)##	0.53 2.44
McDills No 1	Amerada Petroleum (1965)	15–25 (19–22)**	135–187	0.11–0.16
Mokari	French Petroleum (1966)	3.7–10.4		
Macumba	Delhi International (1978)	13	2	0.002
Purni	French Petroleum (1964)	19 (16.2–22)**		
Dalmatia	New (1988)	>20		
CBM93-1	Central Petroleum (2008)	16.7	0.2–96^	1.7×10^{-4}-0.004
CBM107-001	Central Petroleum (2010)		36.7^	0.03

*Hydraulic conductivity values converted from permeability measurements assuming water temperature of 20 °C

**Bracketed porosity values indicate laboratory measurements of core samples, other values derived from geophysical logging

^ Permeability measurements taken over coal measures

#Vertical hydraulic conductivity

Horizontal hydraulic conductivity

2.4.3.2 CROWN POINT FORMATION

The Crown Point Formation is the deepest unit of the Pedirka Basin. The Crown Point Formation unconformably overlies sediments associated with the Early Palaeozoic Amadeus and Warburton Basins. It is widespread and outcrops along the north-western margin of the Pedirka Basin where it borders the Newland Ranges.

A clean sand that occurs at the top of the Crown Point Formation is typically used as a marker for the end of glaciation; this sand unit is regarded as a distinct formation and has been named the Tirrawarra Sandstone, suggesting it is the equivalent of the Tirrawarra Sandstone in the Copper Basin (Wohling et al., 2013). The Crown Point Formation into three sub-units on the basis of lithological variation and log character (Wohling et al., 2013). The basal unit (Unit C) consists of sandstone with interlaminated and interbedded siltstone. The middle unit (Unit B) consists predominantly of siltstone and claystone, while the upper most unit (Unit A) consists of sandstone and interbedded siltstone.

At the time of writing this report, no aquifer tests have been undertaken within the Crown Point Formation. Hydraulic conductivities have been derived from permeability measurements, and these estimates are summarised in Table 2-3.

Table 2-3 Crown Point Formation porosity and permeability values (from Wohling at al., 2013)

Well name	Reference	Porosity (%)	Permeability (mD)	Derived hydraulic conductivity (m/d)*
Mt Hammersley	New (1988)	13.5–24.5	91–1998	0.08–1.66
Colson	Beach Petroleum (1979)	9–13		
Hale River No 1	Amerada Petroleum (1966)	15–22 (11)**	582 (Kv)# 836 (Kh)##	0.49 0.70
McDills No 1	Amerada Petroleum (1965)	15–25		
Mokari	French Petroleum (1966)	2.9		
Macumba	Delhi International (1978)	11–12		
Etingimbra	Osborne and Edwards (1990)	28–30		
Witcherie	French Petroleum (1964b)	(9–21)** V (12–32)** H	557	0.46
Oolarinna	Delhi Petroleum (1985)	8.5–13.4		
Dalmatia	New (1988)	13–18		

*Hydraulic conductivity values converted from permeability measurements assuming water temperature of 20 °C

**Bracketed porosity values indicate laboratory measurements of core samples, other values derived from geophysical logging

^ Permeability measurements taken over coal measures

#Vertical hydraulic conductivity

Horizontal hydraulic conductivity

2.4.3.3 AQUIFER INTERACTIONS BETWEEN PURNI AND CROWN POINT FORMATION

As outlined above, it is presently unclear whether the Purni Formation and Crown Point Formation behave as a single aquifer or whether multiple aquifers and aquitards exist within these formations. In the absence of available hydrogeological data to further characterise these formations, the Purni Formation and Crown Point Formation will be regarded as separate aquifers and will herein be referred to as the Permian aquifers.

A generalised potentiometric surface for the Permian aquifers is given in Figure 2.8. Due to the lack of available monitoring data, it is not possible to produce a potentiometric surface (from Wohling at al., 2013) for a single year or even decade. Water level readings and formation pressures from 1960s onwards have been used to generate the potentiometric surface. Groundwater level observations were corrected to freshwater heads using a method that accounts for changes in water density due to variations in temperature and salinity. The absolute range in groundwater level correction was -0.10 to +0.13 m.

The direction of regional groundwater flow in the Permian aquifers is thought to occur from GAB through northern basin edge and outcropping recharge areas located along the north-western margin to the south-east. The potentiometric surface shown in Figure 2.8 indicates that the north-west region of the Pedirka Basin is either currently, or was in the past, a recharge zone. Local groundwater flow may be influenced by recharge from surface water features along the north-west margin of the basin such as the Finke River and Goyder Creek. Groundwater depth is shallow (less than 10 mbgs) in the vicinity of the Finke River and outcropping Crown Point Formation. Artesian groundwater conditions are expected to occur in the centre and eastern regions of the basin.

The Dalhousie-McDills Ridge is a major structural feature that may influence groundwater flow, however there is limited data available to prove or disprove the influence of this feature. There are just three measurements available for the Permian aquifer within South Australia. These water level estimates are sourced from drill stem tests (DST) undertaken approximately 40 years ago and are considered less reliable than conventional measurements.

Water level measurements for the Permian aquifers and the overlying J aquifer are focused in the north-west area of the basin, with fewer measurements available elsewhere.

2.4.4 Basement

Basement is considered to be the sedimentary deposits in the Warburton Basin and Amadeus Basin, and crystalline basement. The hydrogeological characteristics of basement underlying the Pedirka Basin are poorly understood.

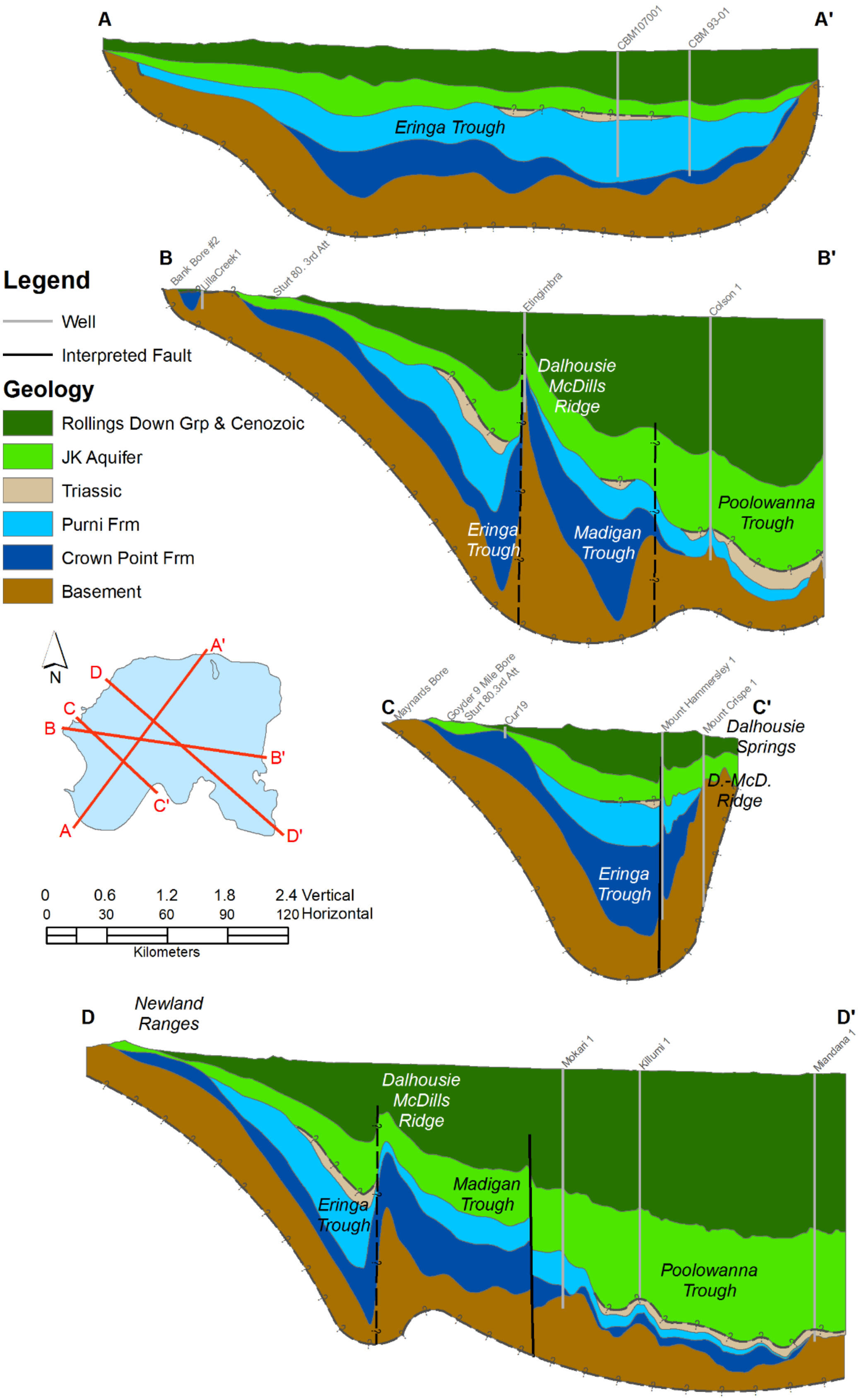

Figure 2.5 **Interpreted cross-sections based on surfaces from seismic and well data (Wohling et al., 2013)**

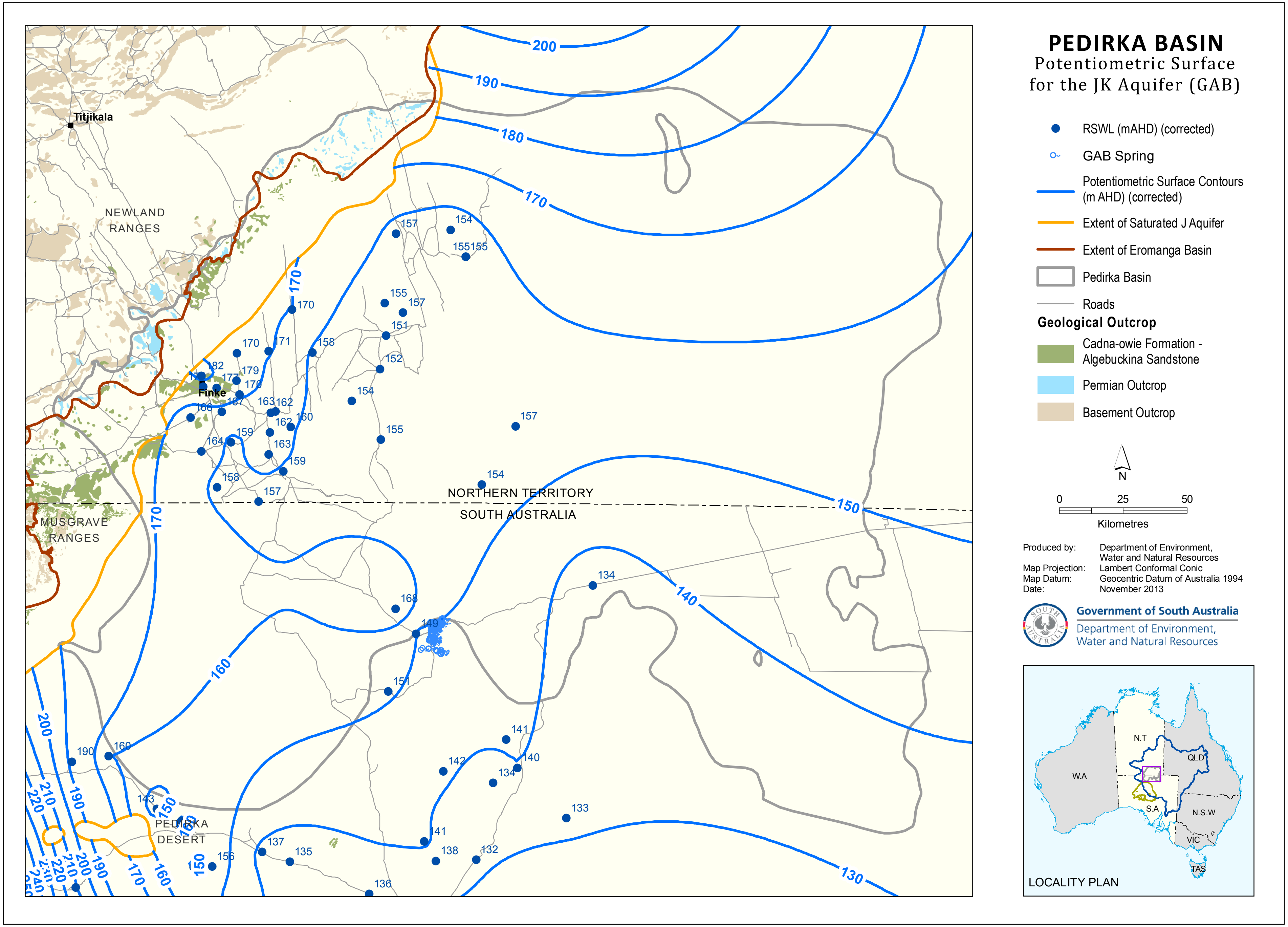

Figure 2.6: Potentiometric surface (corrected) for the J aquifer (GAB) (Keppel et al., 2013)

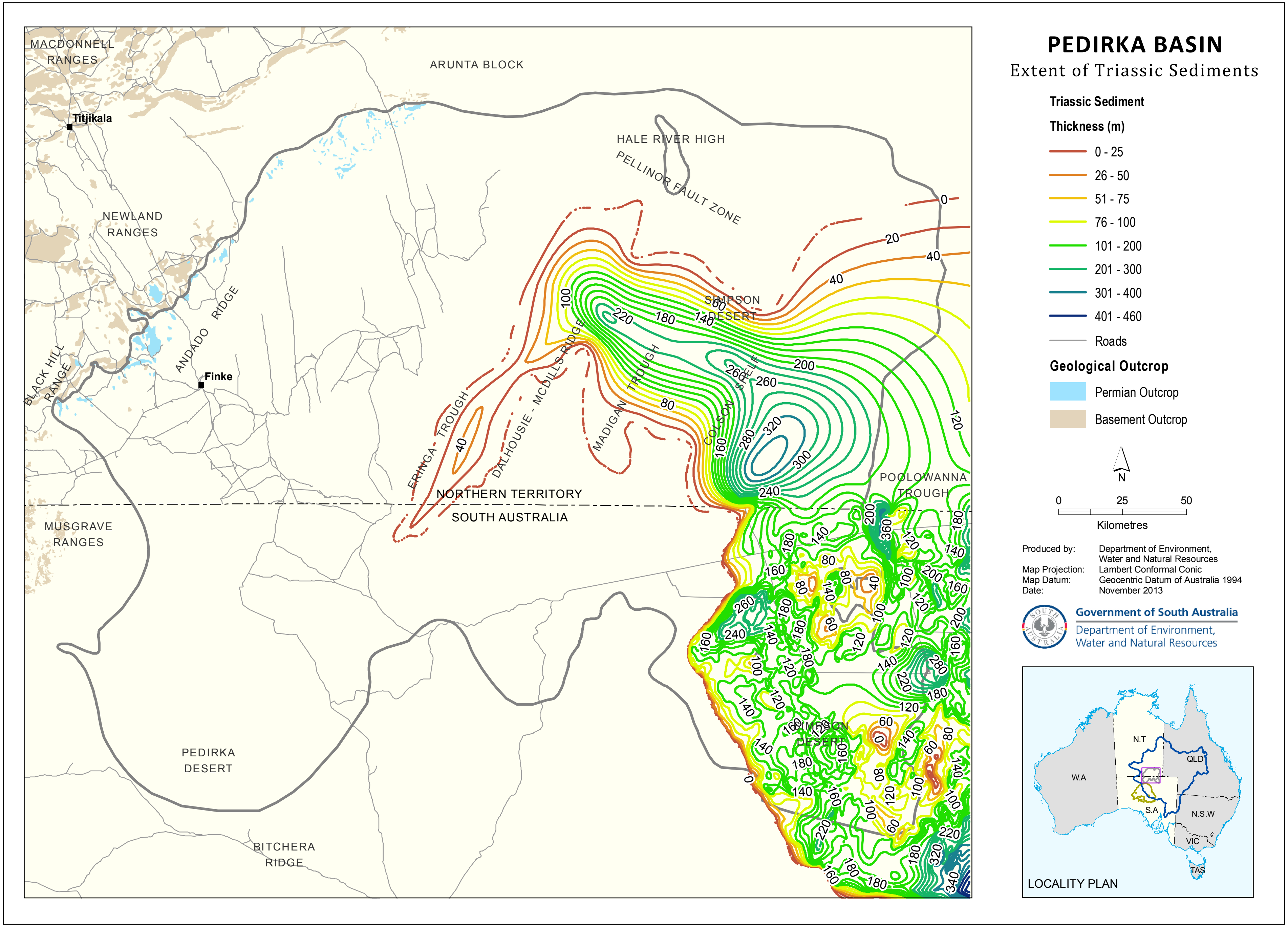

Figure 2.7: Extent and thickness of Triassic sediments

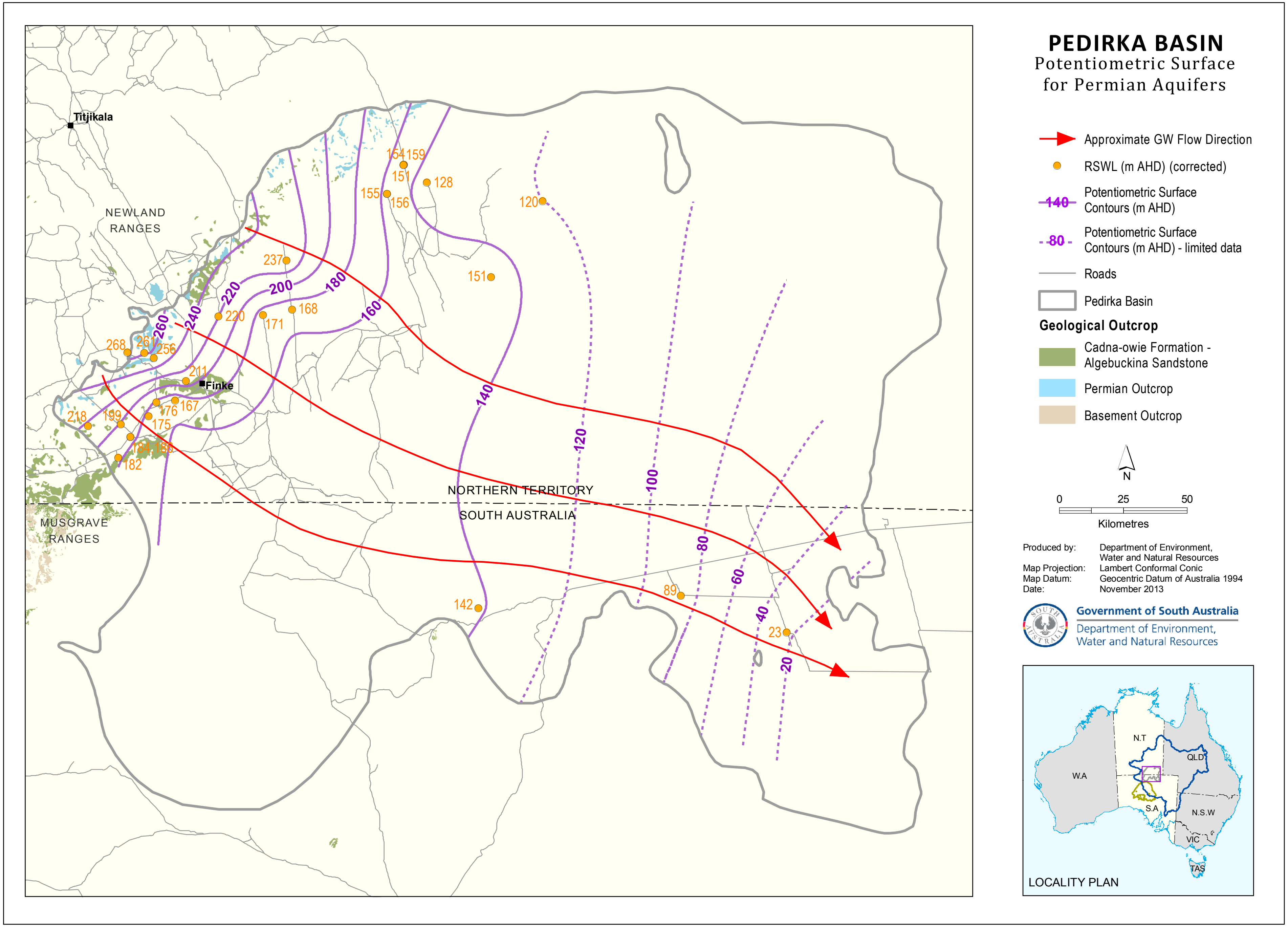

Figure 2.8: Composite potentiometric surface (corrected) for Permian aquifer (Wohling et al., 2013)

2.5 Hydrology

This section describes surface water features, within the extent of the Pedirka Basin, which may interact with groundwater. These include the Finke River and Goyder Creek, which are possible sources of recharge to the basin, and the Dalhousie Springs as a potential groundwater discharge feature.

2.5.1 Finke River and Goyder Creek

The surface water system in the region is characterised by a network of ephemeral rivers and creeks that drain concentrically east towards Kati Thanda-Lake Eyre or one of the other large playas in the region (Figure 2.1). The majority of flow events are short lived, relatively small and occur on either an annual or bi-annual basis (Fulton cited in Wohling et al., 2013).

The Finke River and Goyder Creek are thought to provide potential sources of indirect recharge to the Permian aquifer. Ephemeral river recharge occurs during episodic flow events in arid zone rivers. High groundwater elevations in the Permian aquifer adjacent to the Finke River suggest active recharge is occurring (Figure 2.8).

Annual average rates of recharge from the Finke River within the GAB recharge zone are estimated at between 380 to 850 mm/y, with recharge from a single flow event in 2010 estimated at 1275 mm (Love et al., 2013a). The area over which recharge to the J aquifer occurs where it outcrops along the Finke River has recently been mapped and is approximately 13 km^2.

Potential for recharge to the Permian aquifer exists where drainage lines intersect outcropping Permian sediments or where the Permian aquifer sub-crops beneath permeable sediments (Wohling et al., 2013). Chloride data suggests that recharge from Finke River flows is actively lowering the chloride concentrations in the Permian aquifer. There are no known estimates of recharge to the Permian aquifer from the Finke River. Waterholes identified in the Finke River adjacent to outcropping Crown Point Formation may reflect local discharge from either the Permian aquifers or the Finke River alluvial system (Wohling et al., 2013).

There are no known estimates of recharge to the groundwater system from Goyder Creek, however it is presumed to be less than that of the Finke River on the basis of size and catchment area. Recharge from other surface water features within the basin may occur, such as the lower Hale River, Coglin Creek, Stevenson Creek and Alberga River (Figure 2.1), however there are no data available to make an assessment of the potential connection between the water course and the aquifer.

2.5.2 Dalhousie Springs

The Dalhousie Springs are located at the southern margin of the Pedirka Basin within South Australia. It is the largest spring complex within the western GAB, covering more than 200 km^2 and containing over 114 individual spring vents (Love et al., 2013b). Total discharge to the springs has been estimated at approximately 670 L/s (Habemehl, 1982).

The Dalhousie Springs are located along the Dalhousie-McDills Ridge. Tensional fracturing and faulting associated with the development of the anticline that forms the ridge is surmised as the primary structural contributor to spring conduit formation (Krieg in Wohling et al., 2013). Current scientific understanding of these springs suggests that the majority of water is supplied from groundwater resources in the GAB. Recent analysis of hydrochemical data suggests that the Crown Point Formation may represent a potential source of discharge to the Dalhousie Springs (Keppel et al., 2013). The fracture and fault system associated with the Dalhousie-McDills Ridge was postulated as providing subsurface connection between the Crown Point Formation and the spring complex.

2.6 Diffuse recharge

Diffuse recharge is defined as recharge to an aquifer resulting from rainfall infiltrating the soil surface and percolating through the unsaturated zone to the water table. Investigation of potential diffuse recharge occurring within the western GAB suggests that virtually no recharge has occurred over the last 10 000 years and ephemeral river recharge may be the only source of modern day recharge to the basin along the western margin (Keppel et al., 2013).

Modern day recharge is thought to be less than discharge, and the basin is in a state of long-term pressure decline as a result of declining rainfall over the recent climate cycle (last 10 000 years or earlier). Modern-day diffuse recharge is assumed to be negligible. In view of this, the diffuse recharge rate applied in the model includes a decline at a rate of 1 mm per 1000 years. Outcomes from a numerical modelling exercise for the GAB suggests that the water level decline in a large confined system may take 50 000 to 60 000 years to stabilise (Keppel et al., 2013).

The groundwater flow pattern presented in Figure 2.8 supports the north-west margin of the Pedirka Basin as a recharge zone. However it is unclear whether recharge is occurring under current arid climatic conditions or has occurred sometime in the recent geological past. Diffuse recharge has been estimated from 11 bores using a saturated chloride mass balance (CMB) approach at between 0.02 mm/y and 0.16 mm/y (Figure 2.9), suggesting that modern diffuse recharge is negligible. The area over which diffuse recharge is occurring or has occurred in the past is not known with certainty.

2.7 Groundwater pumping

There is limited knowledge of groundwater extraction within the Pedirka Basin. Groundwater extraction is thought to occur from reliable groundwater resources within discrete Cainozoic aquifers and the J aquifer within South Australia and the Northern Territory. Groundwater extraction from the Permian aquifer is thought to occur exclusively along the western margin of the Pedirka Basin within the Northern Territory, where it is used as a source of stock water for pastoral enterprises and provides a water supply for several Aboriginal outstations west of Apatula (Finke) Community (Wohling et al., 2013).

Volumes of groundwater extracted from the aquifers within the study extent are not known with certainty. Groundwater extraction is predominantly for stock and domestic uses.

2.8 Groundwater salinity

Groundwater salinity measured from bores constructed in the Crown Point Formation along the north-western margin of the basin range from 93 mg/L to 7910 mg/L with an average salinity of 2470 mg/L (Wohling et al., 2013). Fresher salinities are encountered in wells adjacent to the Finke River and Goyder Creek, where five wells contain potable groundwater with salinity of less than 500 mg/L.

Limited hydrochemistry data is available for the Crown Point Formation outside the north-west margin of the Pedirka Basin. One exploration well in the center of the basin (McDills No. 1) has a recorded salinity of 2425 mg/L for the Permian sequence. Analysis of six groundwater samples obtained during a DST report a salinity range of 1 084 mg/L to 14 980 mg/L and an average salinity of 8900 mg/L. DST results have the potential to be contaminated by drilling fluids and are therefore of much poorer quality than samples obtained from conventional groundwater wells (Wohling et al., 2013)

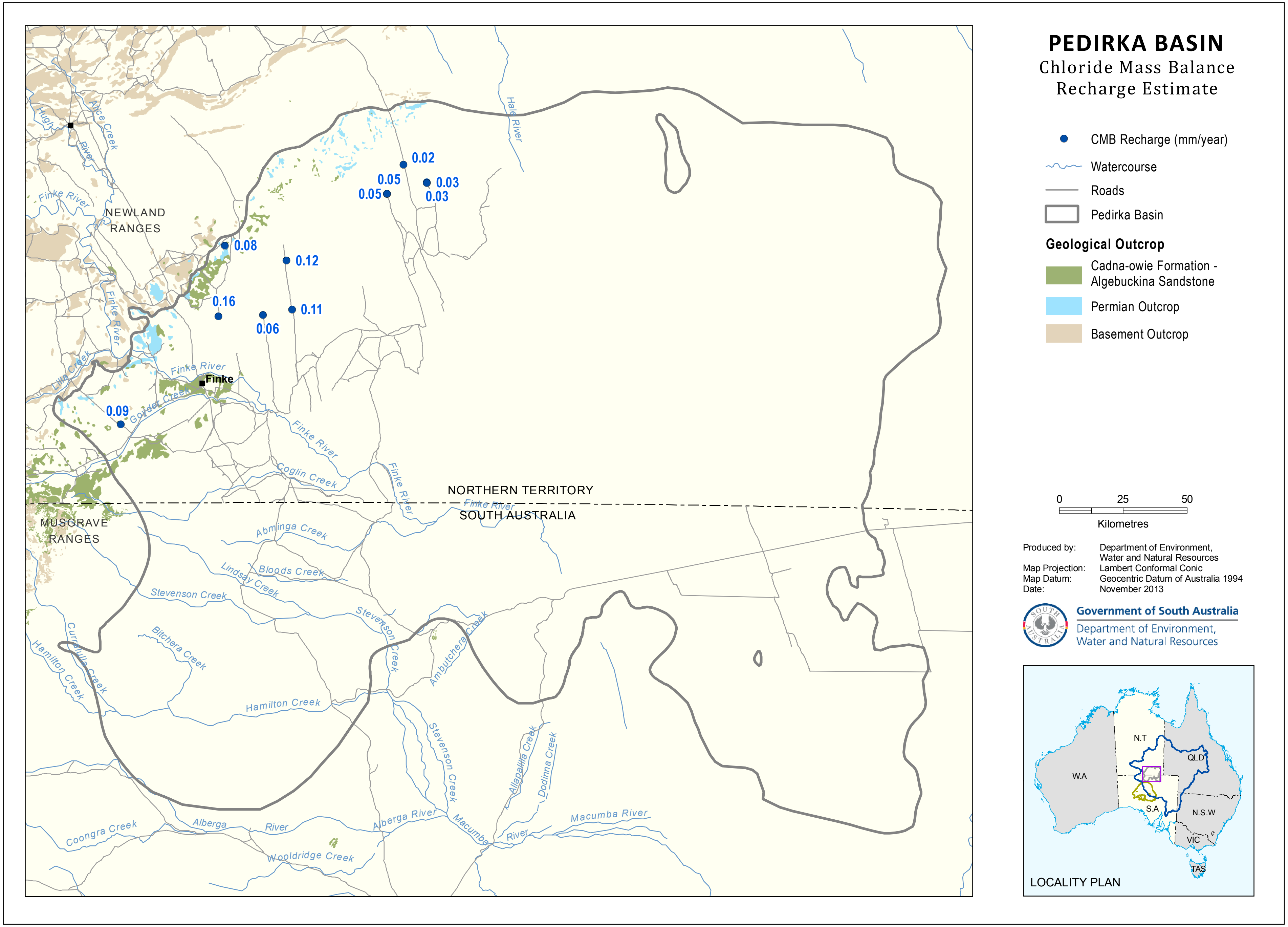

Figure 2.9: Chloride mass balance recharge estimate (mm/year)

2.9 Conceptual groundwater model

Figure 2.10 and Figure 2.11 illustrate the current conceptualisation of the hydrogeology of the Pedirka Basin. Shape and structure of the basin is influenced by faults and folds, including the structural feature known as Dalhousie-McDills Ridge.

Flow direction

According to current water level data, groundwater flow direction is predominantly occurring from the north-west to the south-east, with some lateral inflow from the north via the J aquifer.

Current groundwater flow direction is highlighted by diffuse recharge that is occurring, or has occurred in the past, along the north-west margin of the basin and discharge which mainly occurs along the southern edge of the basin through lateral outflow via the GAB aquifer.

Aquifer interaction

Insufficient lithological data and knowledge is available to develop a regional understanding of whether the Purni Formation and Crown Point Formation behave as a single aquifer, or whether multiple aquifers and aquitards exist within these formations. Within the eastern portion of the basin, Triassic sediments of the Simpson Basin unconformably overly Permian sediments. It is postulated that the Triassic may limit the hydraulic connectivity between the Permian aquifer and the overlying J aquifer, however faulting may enable vertical localised connectivity between overlying and underlying aquifers, particularly in the location of the Dalhousie-McDills Ridge.

Along the west and northwest margins of the basin there is potential for interaction between basement and the GAB aquifer and Permian aquifers.

Recharge

Recharge occurs on the north-west margin of the basin and include lateral inflow from GAB and recharge from rainfall and streams. It is presumed that diffuse recharge has been declining over the recent climate cycle (last 10 000 years) due to reduced rainfall. Based on current understanding, modern diffuse recharge is approximately 0.1 mm/y, which is negligible. Recharge from surface water features occurs where the Finke River and Goyder Creek intersect outcropping J aquifer and Permian aquifer, and is thought to be the primary mechanism for modern-day recharge to the basin. Indirect recharge from surface water features may also occur via the J aquifer to the Permian aquifer.

Discharge

Discharge mechanisms are uncertain, as the South Australian portion of the Pedirka Basin is data poor.

In the north-west of the Pedirka Basin localised discharge may occur via evapotranspiration where the watertable is relatively shallow near Finke River. Local discharge to waterholes may also occur. These processes are assumed to be minor components of the overall basin water balance.

The Rolling Downs Group controls the rate of vertical discharge from the J aquifer to shallower aquifers within the Cainozoic sediments. Estimated rates of diffuse discharge through the Rolling Downs Group range between 3×10^{-4} to 5×10^{-4}, but can be higher where preferential flow paths occur along fractures and major faults such as the Dalhousie-McDills Ridge (Love et al., 2013b). This may influence groundwater flow direction and vertical discharge.

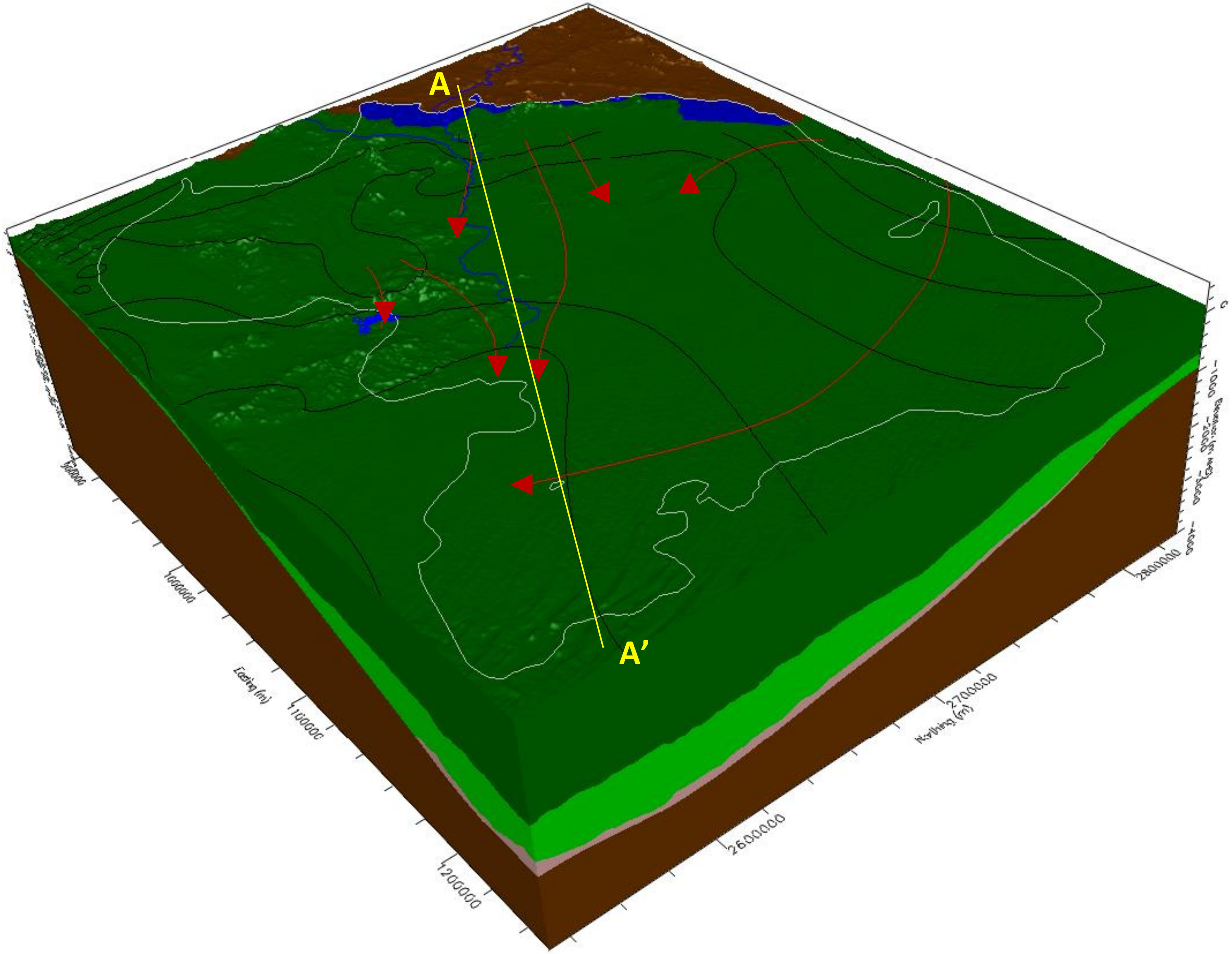

Figure 2.10 Pedirka Basin conceptual diagram A

**vertical exaggeration 25x*

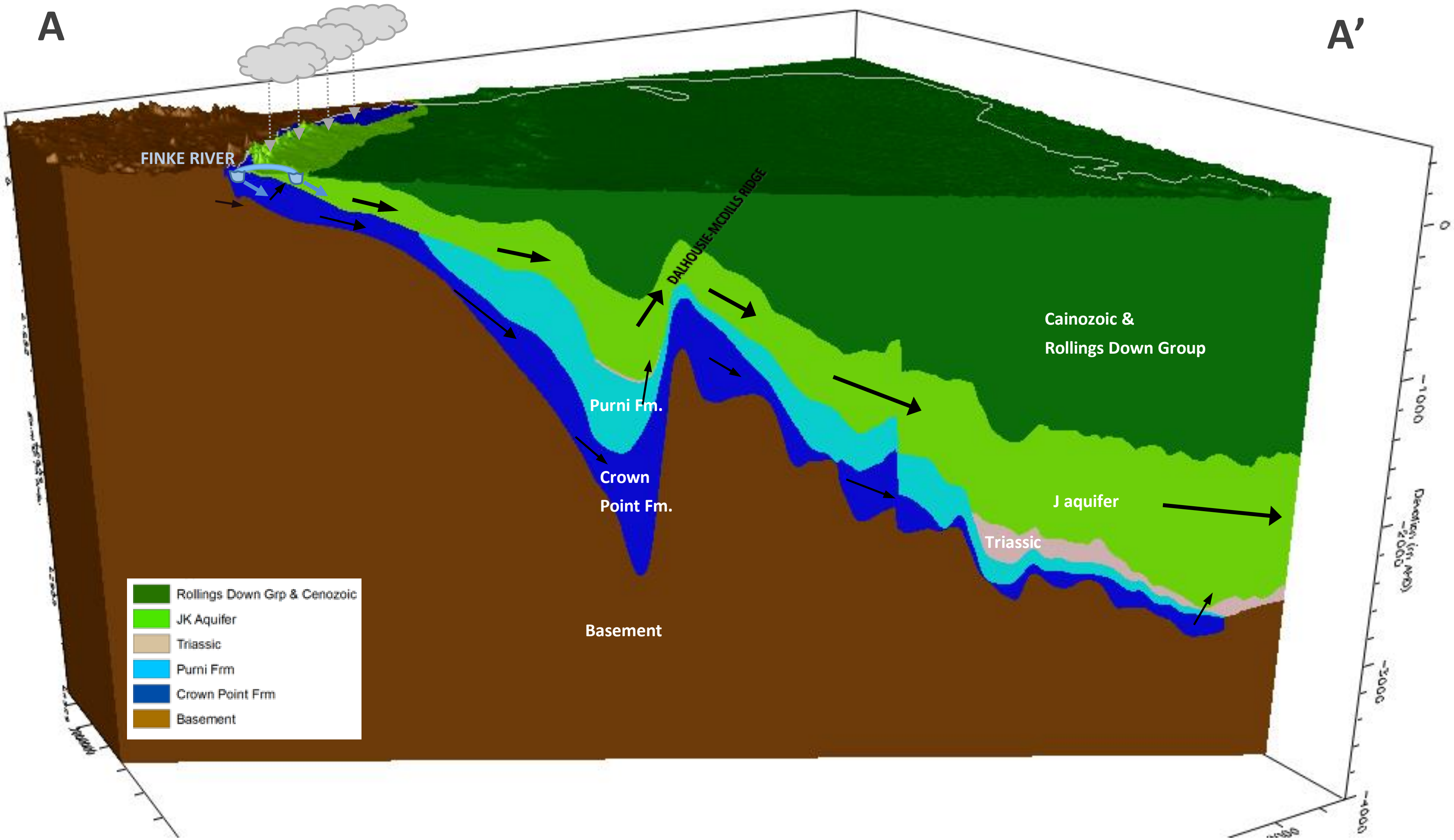

Figure 2.11 Pedirka Basin conceptual diagram B

**Diagram for illustrative purposes only. Vertical exaggeration 50x. Annotation features not to scale – arrows indicate direction, not magnitude.*

3 Model construction

The purpose of the modelling exercise was to aid the current conceptual understanding of the Pedirka Basin, provide an estimation of regional-scale water balance, and use sensitivity tests to identify which hydrogeological factors most likely control the hydrogeological system in the Pedirka Basin.

The modelling exercise packaged existing data, knowledge and information for future modelling and other projects. It also identified key data and knowledge gaps, which can direct future planning of field investigations in the Pedirka Basin.

The groundwater model developed for Pedirka Basin is considered a regional scale, elementary model, defined as Class 1 (Barnett et al., 2012).

3.1 Modelling reference group

A modelling reference group was formed at the commencement of the project. The purpose of setting up the reference group was to fill in data and knowledge gaps where possible and provide feedback regarding conceptualisation of the groundwater flow system, modelling approach and model development.

The reference group acknowledged that the design of the groundwater model for the Pedirka Basin was consistent with the aims of the modelling exercise, the data and information available and the project budget and timeframe. Modelling assumptions, simplifications and approach were discussed and agreed to by the reference group, such as:

- Model layering and assumption of no interaction between the J aquifer and shallower aquifers
- Selection of aquifer and aquitard parameters and the modelling process
- Regional boundary conditions representing regional flow into and out of the model domain
- Exclusion of Dalhousie Springs as a model boundary condition
- Declining diffuse recharge rate
- Approach to sensitivity testing and variation of parameters and stresses.

The reference group acknowledged that the groundwater model developed for the Pedirka Basin is an adequate starting point, and that the model should be refined in the future as more data and knowledge is gained to better constrain the model and improve the representation of the physical system.

3.2 Modelling package and front end

MODFLOW was selected as the numerical code for groundwater flow modelling of the Pedirka Basin due to its reliability, consistency, stability and to fit the purpose for this project. MODFLOW is a three-dimensional finite difference code developed by the US Geological Survey (McDonald and Harbaugh 1988).

The standard version of MODFLOW simulates flow exclusively within the saturated zone and no density impact is considered. Density effects due to groundwater temperature and salinity may influence flow in the Pedirka Basin. It is considered that, due to the magnitude of uncertainty in key processes and measured parameters, the substantial additional effort required to simulate effects of density would not be justified for the purpose of the project.

The numerical solver chosen was MODFLOW PCG2, with a head change criterion set to 0.01 m and a maximum absolute change in residual of 1 m^3/d selected.

Environmental Systems, Inc. (ESI) Groundwater Vistas Version 6 (Rumbaugh & Rumbaugh, 2000) was selected as a pre and post processor and Schlumberger Water Services Visual MODFLOW package was used to assist in model testing and to develop figures and 3-D visualisations for the report.

3.3 Model domain and grid

The model domain simulates an area 357.5 km east–west by 298 km north–south with coordinates of the model origin at E894000 N2532000 (GDA 1994 South Australian Lambert) (Figure 3.1). As is a common modelling practice, the model domain was designed larger than the basin and includes regions situated outside of the Pedirka Basin at a minimum distance of 5 km from the basin boundaries.

The rectangular model grid is divided into 715 columns, 596 rows, and uniform model grid of 500 × 500 m. The reason for using a 500 m cell size is to provide a sufficient resolution for representation of basin architecture.

Six model layers are included in the model with five active layers (see Section 3.5), resulting in 2 130 700 finite difference cells. A cross-section of the model layer from the western margin of the basin to the eastern margin is shown in Figure 3.2.

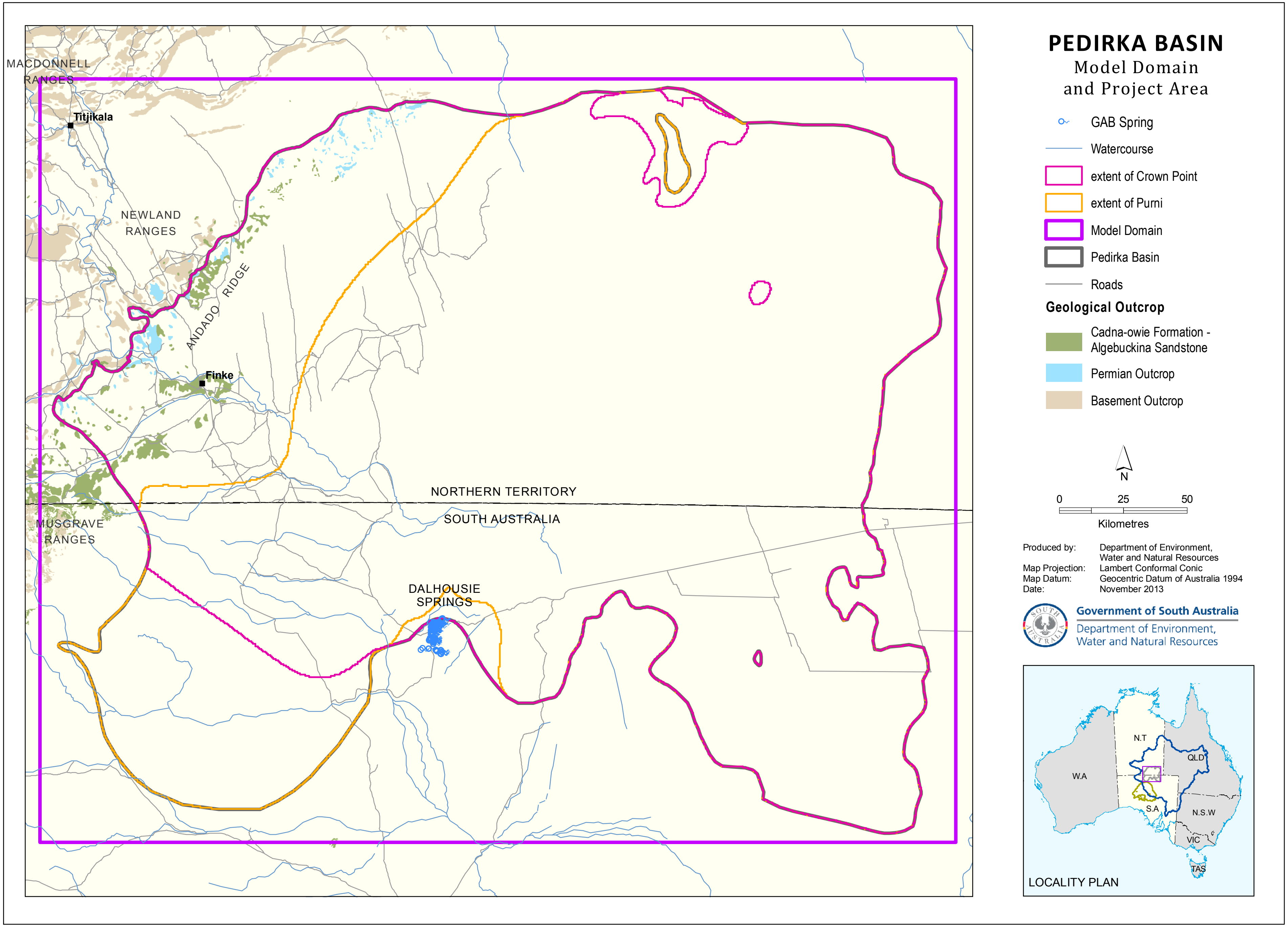

Figure 3.1: Model domain and project area

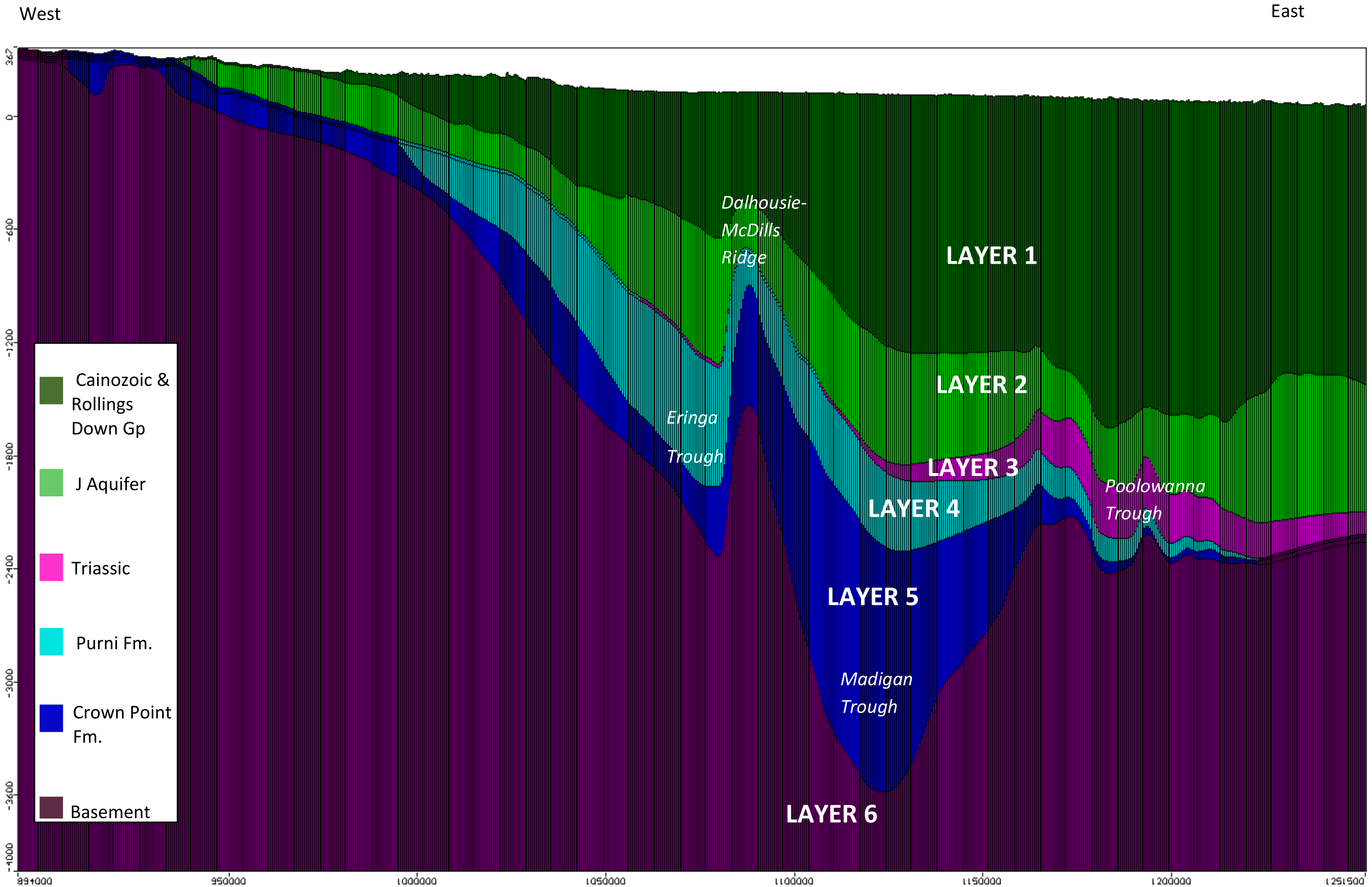

Figure 3.2 Model layers (cross-section along row 245)

3.4 Model stress periods and initial conditions

For the purposes of the project, both a steady state and a transient model are developed. The steady state model is independent of time and represents long term average conditions in the basin which are assumed to have occurred in the past, including greater diffuse (rainfall) recharge. The steady state solution for head is provided as initial conditions to the transient simulation. This is common modelling practice and is explained further in Barnett et al. (2012).

The transient model simulates a period of 100 000 years to represent changing conditions in the hydrogeological system and includes representation of the past, current and future conditions. The transient model stress periods vary to capture important trends in aquifer pressure head and water balance.

3.5 Model layers

The groundwater model for the Pedirka Basin represents six key hydrogeological units with five active model layers (Layers 2 to 6). Model layers are described in Figure 3.2 and Table 3-1. The layering chosen includes the major regional hydrogeological units to the best of current data, knowledge and information.

Table 3-1 Model layer aquifers and aquitards within Pedirka Basin

Layer	Hydrogeological group or unit	Aquifer / aquitard	MODFLOW layer type
1	Cainozoic and Rolling Downs Group	Aquitard	Inactive
2	J Aquifer	Aquifer	Type 0 (confined)
3	Triassic	Aquitard	Type 0 (confined)
4	Purni Formation	Aquifer	Type 0 (confined)
5	Crown Point Formation	Aquifer	Type 0 (confined)
6	Basement	Aquitard (leaky)	Type 0 (confined)

Layer 1 (Rolling Downs Group and Cainozoic) is included in the model for completeness, but it is assigned as inactive, or no-flow. Due to the low permeability of the Rolling Downs Group it is assumed that there is very minor interactions between the underlying J aquifer and shallower interbedded aquifers in the Cainozoic and Rolling Downs Group. This assumption/simplification reduces model complexity associated with shallower aquifers and ensures stability of the model.

All five active model-layers (Layers 2 to 6) are modelled as confined (type 0) which represents the aquifer layer conditions across most of the basin area, improves model stability and reduces computation time. Modelling the aquifer system as confined is considered suitable over most of the basin, but the aquifers are unconfined/confined in a small area along the north-west margin of the model domain. The model may slightly overestimate aquifer transmissivity and underestimate aquifer storage in this area. The impact of this simplification/assumption was addressed through an uncertainty analysis discussed in a later section.

The structure of model layers consider topographic variation, drillhole data, seismic data and hydrogeological understanding of faulting and deposition (Wohling et al., 2013). Formation surfaces were modified to prevent negative model layer thickness and very thin model layers in the north-west of the Pedirka Basin.

Further explanation of surfaces of active model layers (Layers 2–6) is given in Section 3.5.2**Error! Reference source not found.** to 3.5.6.

3.5.1 Layer 1: Cainozoic and Rolling Downs Group

The Rolling Downs Group acts as a confining layer with vertical hydraulic conductivity ranging between 3.46×10^{-9} m/d and 8.64×10^{-9} m/d (Keppel et al., 2013). To avoid the computation instability but to keep the model layer surface for completeness (especially bottom of model Layer 1 / top of model Layer 2), Layer 1 is included in the model but assigned as inactive. The layer surface is completed in the project so that Layer 1 can be changed to an active layer if required. Subject to additional information, Layer 1 could be split into two discrete layers separating the aquifers of the Cainozoic from the aquitards of the Rolling Downs Group.

3.5.2 Layer 2: J Aquifer

Layer 2 represents the J aquifer. A surface representing the top of Layer 2 was generated using data describing the elevation of Permian sediments (Wohling et al., 2013) and adding the thickness of the J aquifer (Sampson et al. 2012). Where the J aquifer is known to be absent along the north-west margin of the Pedirka Basin, the top of Layer 2 is extrapolated from the edges of the basin and the layer is given properties of Crown Point Formation where it outcrops, and properties of basement outside of the Pedirka Basin.

The elevation of Layer 2 ranges between -1855 m AHD in the south-east and 500 m AHD in the north-west (Figure 3.3). Layer 2 is thinnest in the north-west (minimum modelled thickness of 10 m) and thickens toward the south-east of the model extent, reaching a maximum thickness of 1150 m (Figure 3.8).

3.5.3 Layer 3: Triassic

Layer 3 represents Triassic sediments of the Simpson Basin that are generally limited to the Poolowanna Trough, Madigan Trough and are thinly deposited within the Eringa Trough (Figure 3.4). It is assumed that the Triassic behaves as an aquitard which limits vertical flow between the Permian aquifer and the J aquifer.

The surface elevation of Layer 3 was generated using data describing the elevation of Permian sediments (Wohling et al., 2013) and recently mapped extent and thickness of the Triassic. Where the Triassic is mapped as absent, the surface elevation of Layer 3 is assumed to be approximately 10 m above the surface elevation of Permian sediments (Layer 4) and the layer adopts hydraulic properties equivalent to Layer 4 (Permian aquifer or basement).

The elevation of Layer 3 ranges between -2900 m AHD in the south-east and 450 m AHD in the north-west (Figure 3.4). Where the Triassic is present, it is thickest immediately east of the Colson Shelf, reaching a maximum thickness of 350 m (Figure 3.9).

3.5.4 Layer 4: Purni Formation

Layer 4 represents the Purni Formation of the Pedirka Basin. A surface representing the top of Purni Formation was generated from interpretation of drillhole and seismic data (Wohling et al., 2013). Where the Purni Formation has been mapped as absent, the top of Layer 4 represents the Crown Point Formation. In areas where the Purni Formation is absent, Layer 4 adopts equivalent hydraulic properties to Layer 5 (Crown Point Formation). Outside of the basin extent, the top elevation of Layer 4 is extrapolated from the basin margin and the layer is given hydraulic properties of basement.

The elevation of the top of Layer 4 ranges from -2920 m AHD in the south-east to 450 m AHD in the north-west (Figure 3.5). The maximum thickness of Layer 4 is 850 m, in the location of the Eringa Trough (Figure 3.10).

3.5.5 Layer 5: Crown Point Formation

The top of Layer 5 was generated using data describing the elevation of the surface of the Crown Point Formation (Wohling et al., 2013). Where the Crown Point Formation has been mapped as absent, which includes in the south-east of the basin and along the Hale River High, the top of Layer 5 is assumed to be 10 m above the elevation of basement. The layer adopts basement hydraulic properties in these areas.

The elevation of the top of Layer 5 ranges from -2930 m AHD in the south-east to 450 m AHD in the north-west (Figure 3.6). Layer 5 is thinnest along the north-west margin of the basin, with a minimum modelled thickness of 10 m. Layer 5 is thickest immediately north of the Dalhousie-McDills Ridge, reaching a maximum thickness of 1700 m (Figure 3.11).

3.5.6 Layer 6: Basement

Layer 6 represents basement, including the Warburton Basin, Amadeus Basin and crystalline Oroterogoic (basement) rock. The top of Layer 6 was generated using data describing the elevation of the base of Permian sediments (Wohling et al., 2013). Outside of the basin extent, the top elevation of Layer 6 is extrapolated from the basin margin (interpolated based on the nearest elevation of the base of Permian sediments at the edge of the basin).

The surface elevation of Layer 6 is presented in Figure 3.7. Elevation ranges from -3800 m AHD north of the Dalhousie-McDills Ridge to 450 m AHD in the north-east of the model extent. A uniform bottom elevation of Layer 6 of -4000 m AHD has been used as the base of the model.

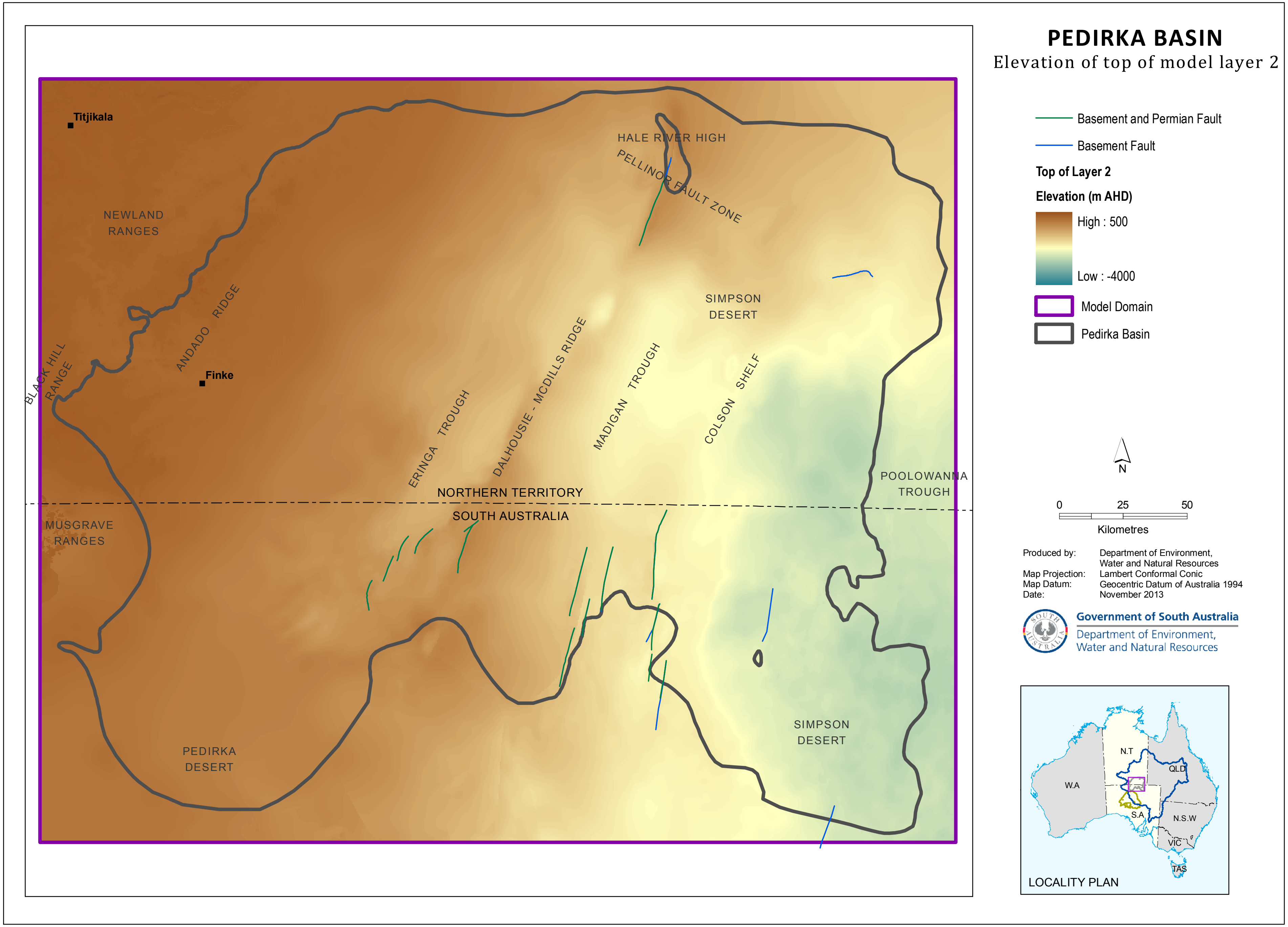

Figure 3.3: Elevation of top of model layer 2 (m AHD)

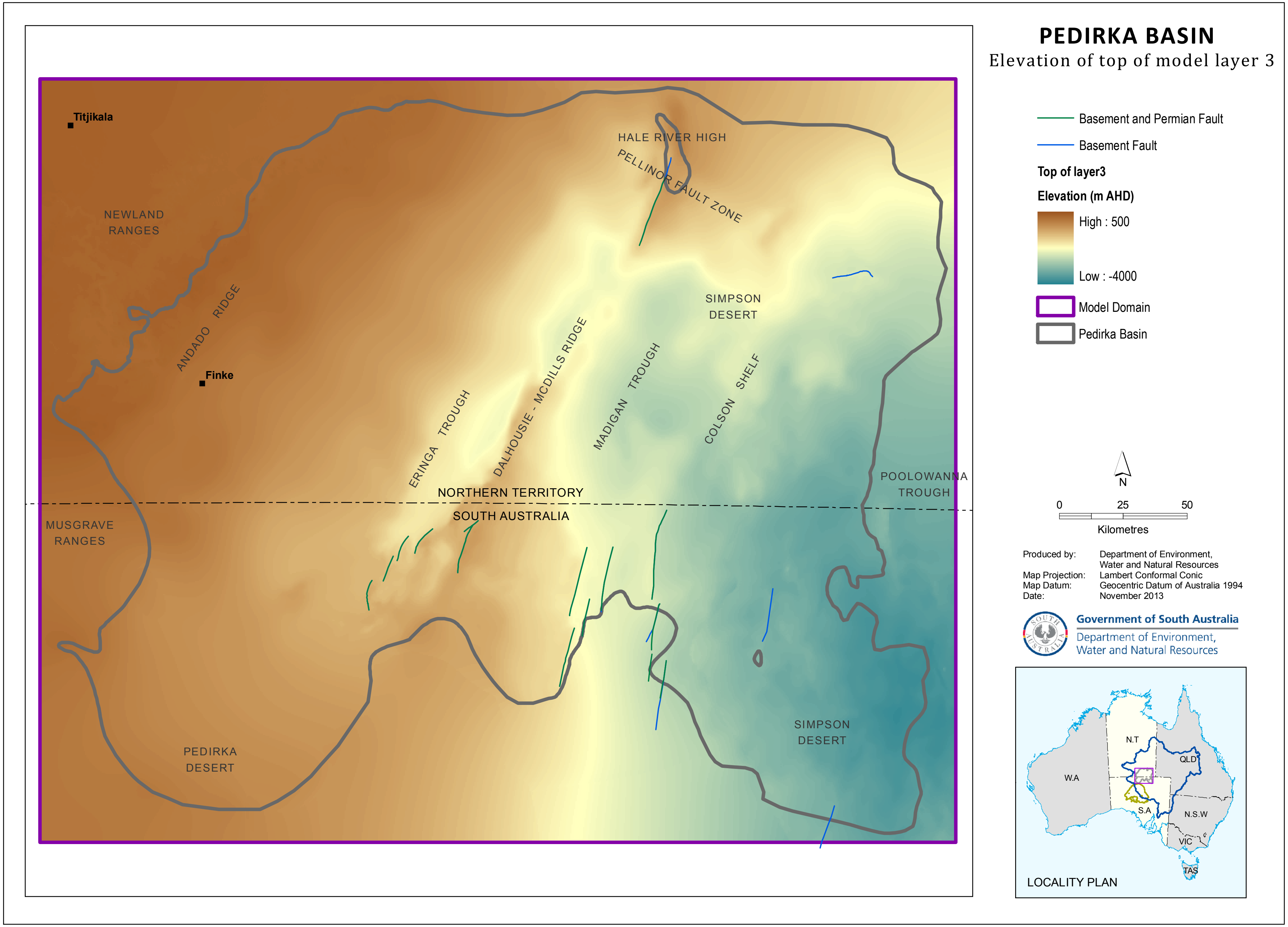

Figure 3.4: Elevation of top of model layer 3 (m AHD)

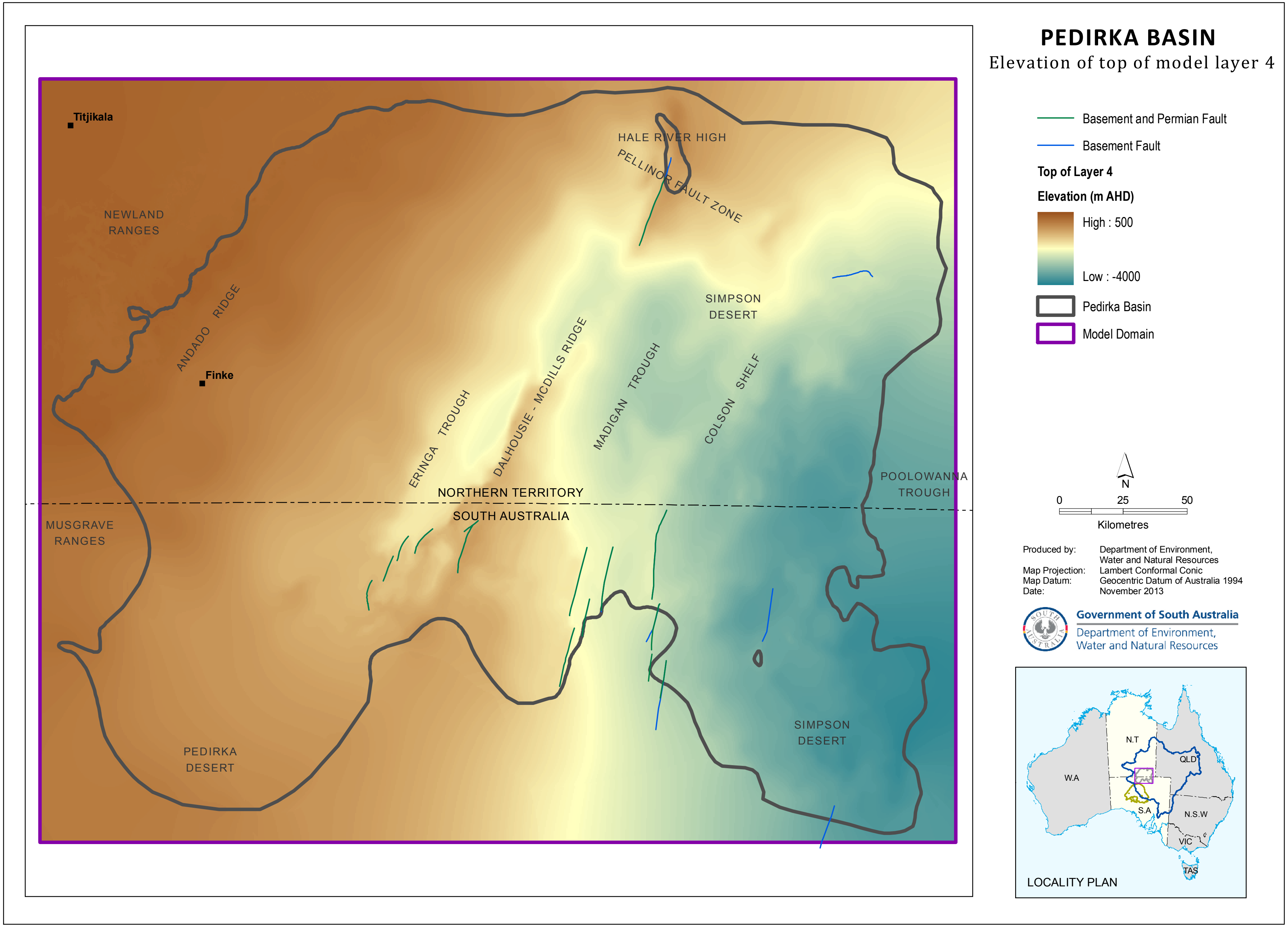

Figure 3.5: Elevation of top of model layer 4 (m AHD)

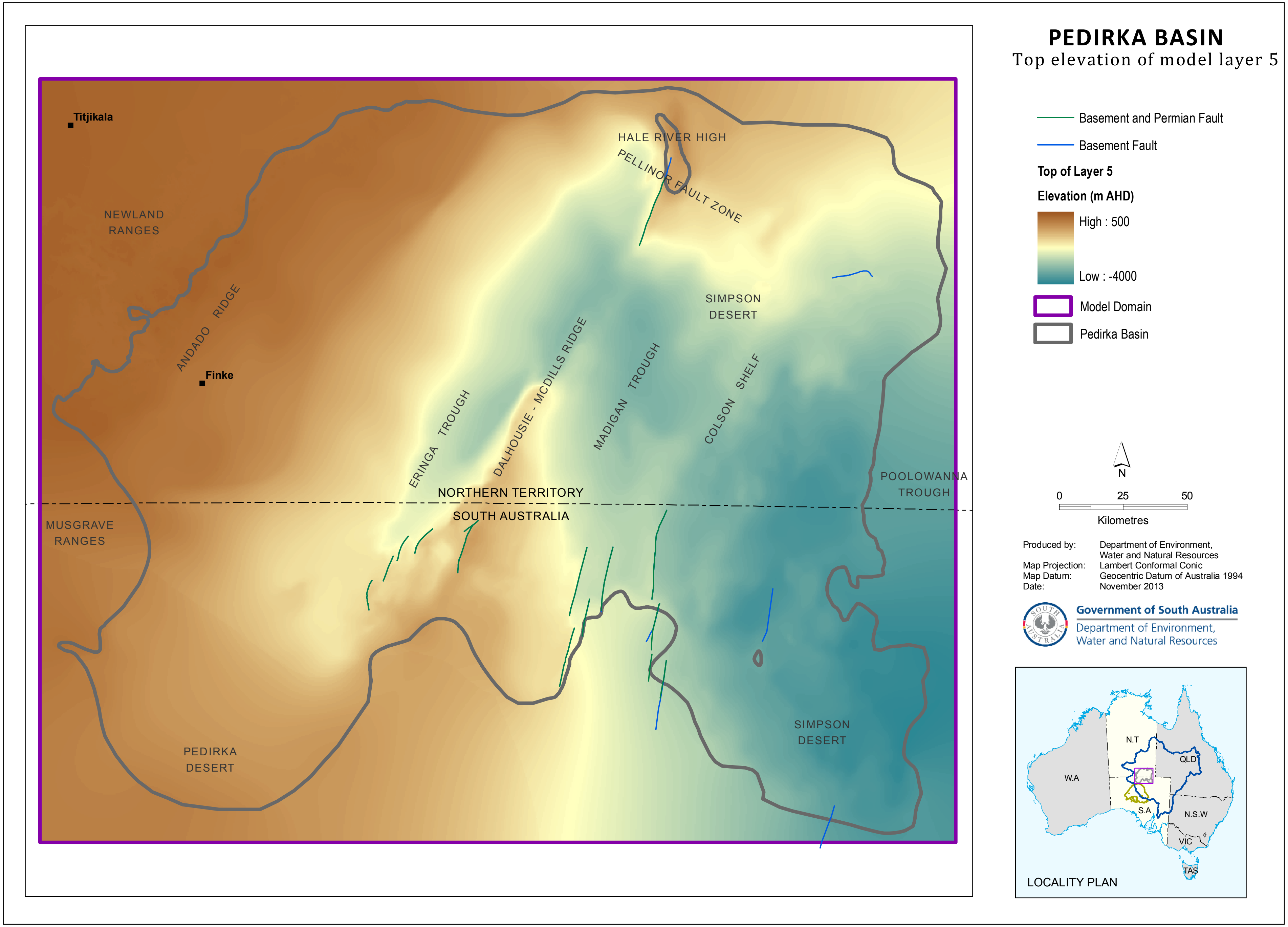

Figure 3.6: Top elevation of model layer 5 (m AHD)

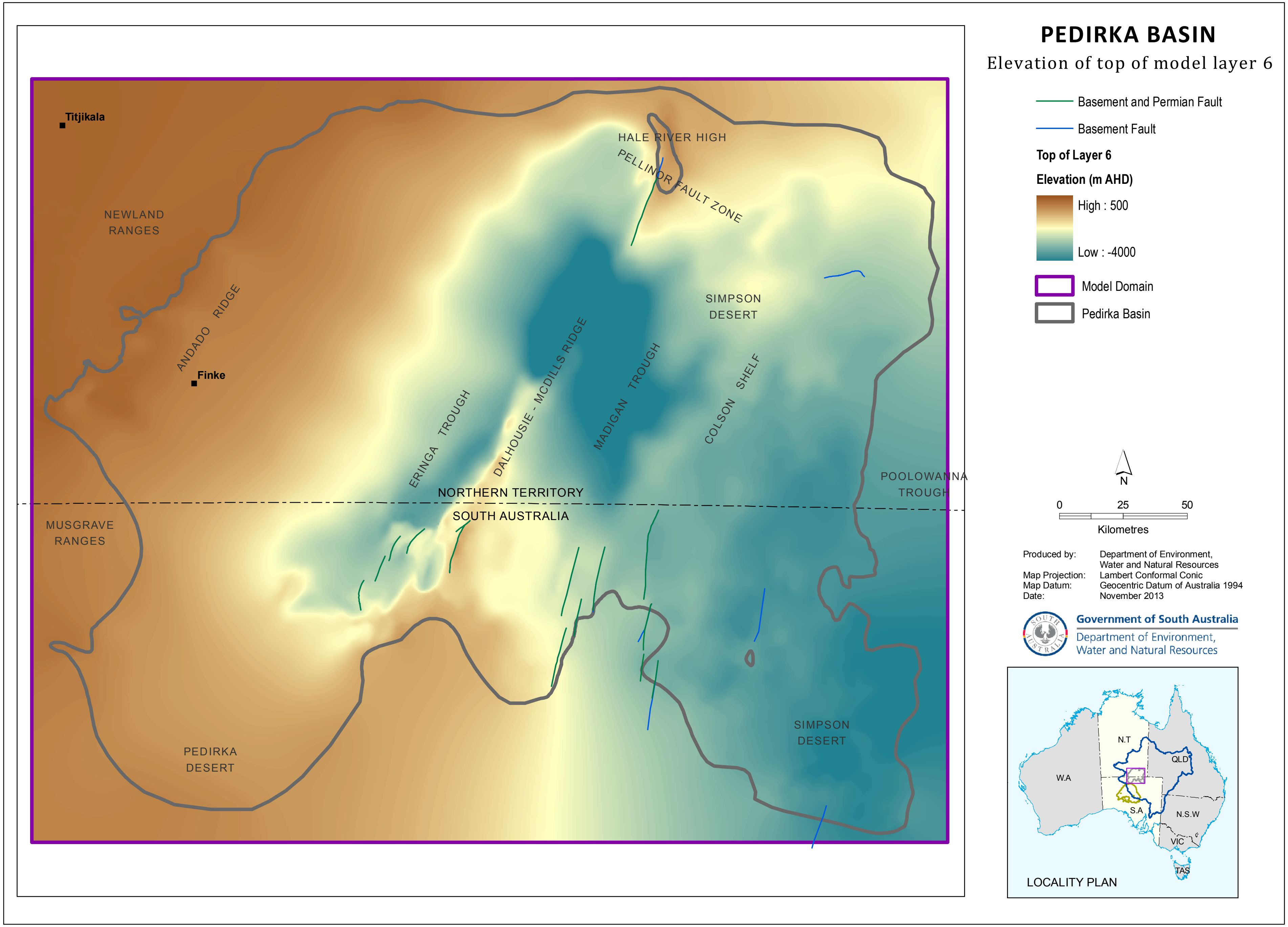

Figure 3.7: Elevation of top of model layer 6 (m AHD)

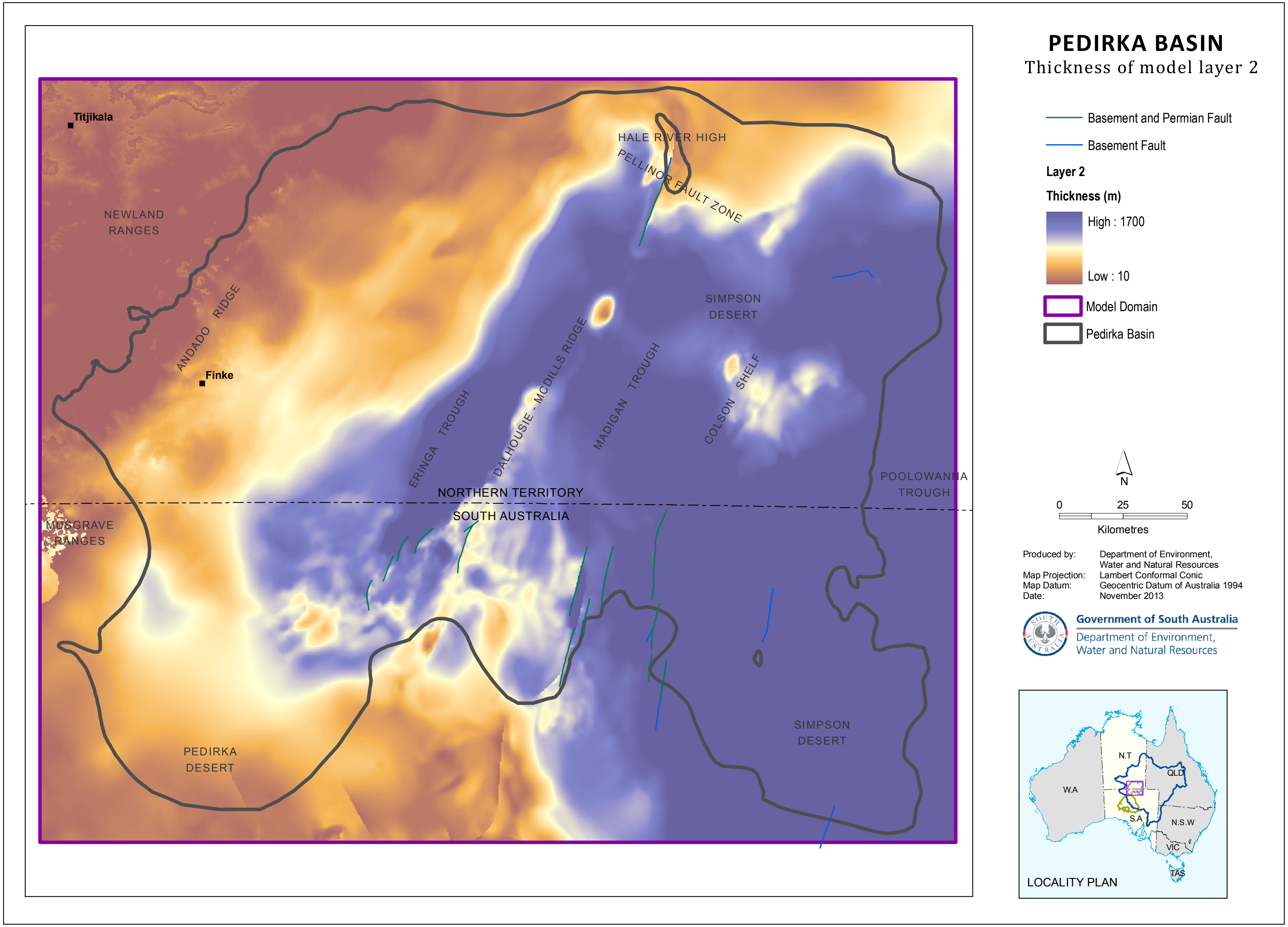

Figure 3.8: Thickness (m) of model layer 2

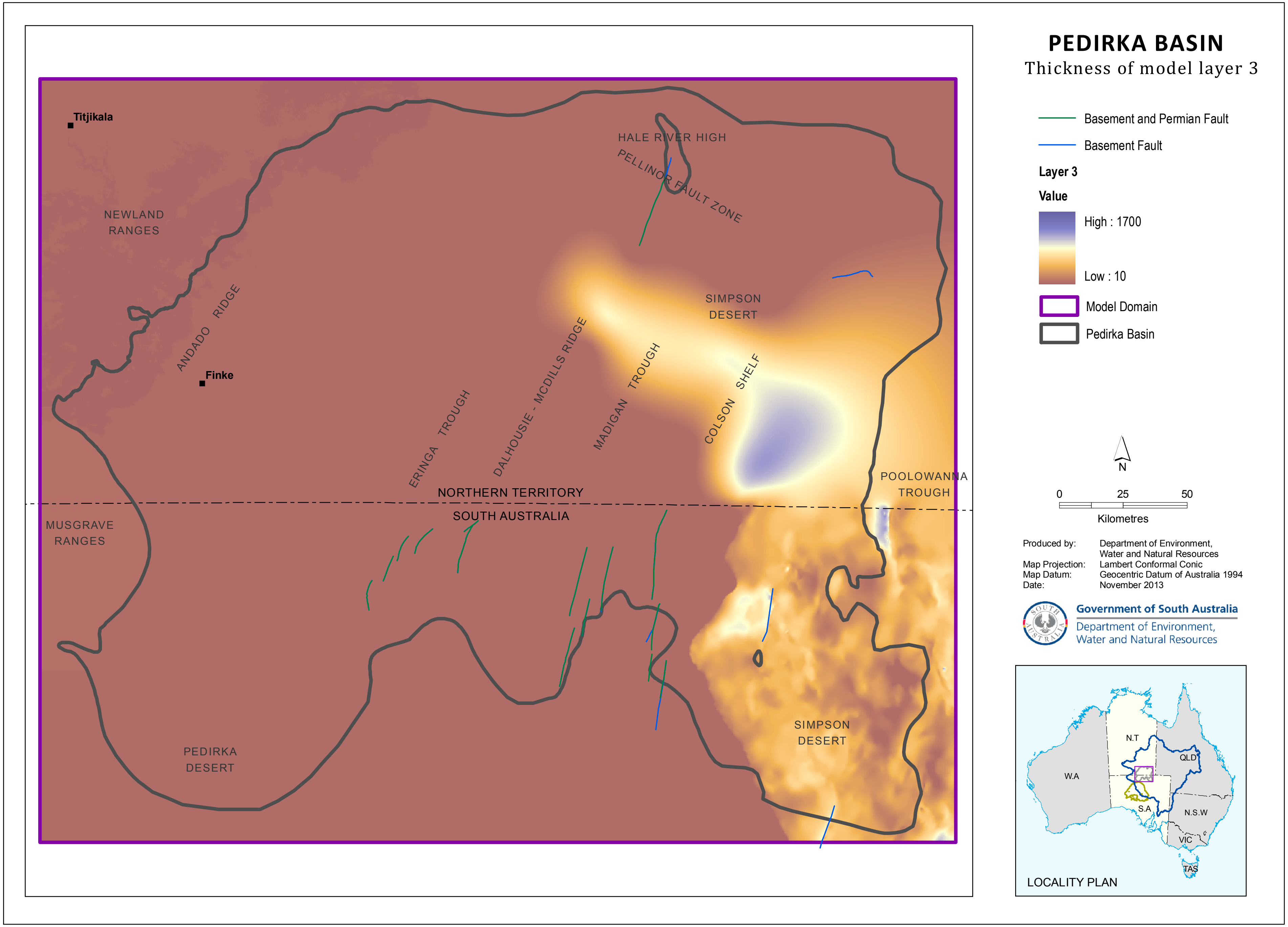

Figure 3.9: Thickness (m) of model layer 3

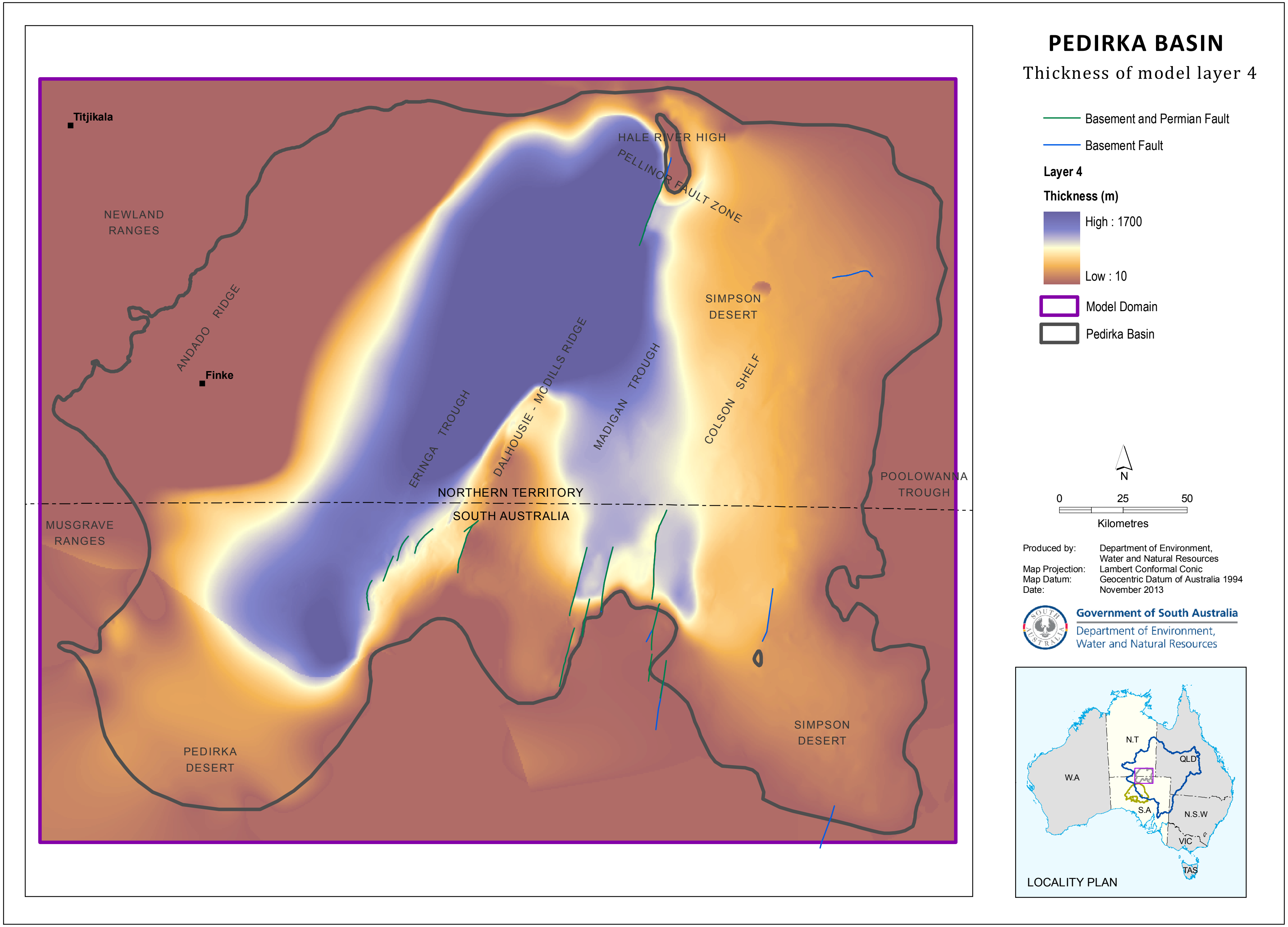

Figure 3.10: Thickness (m) of model layer 4

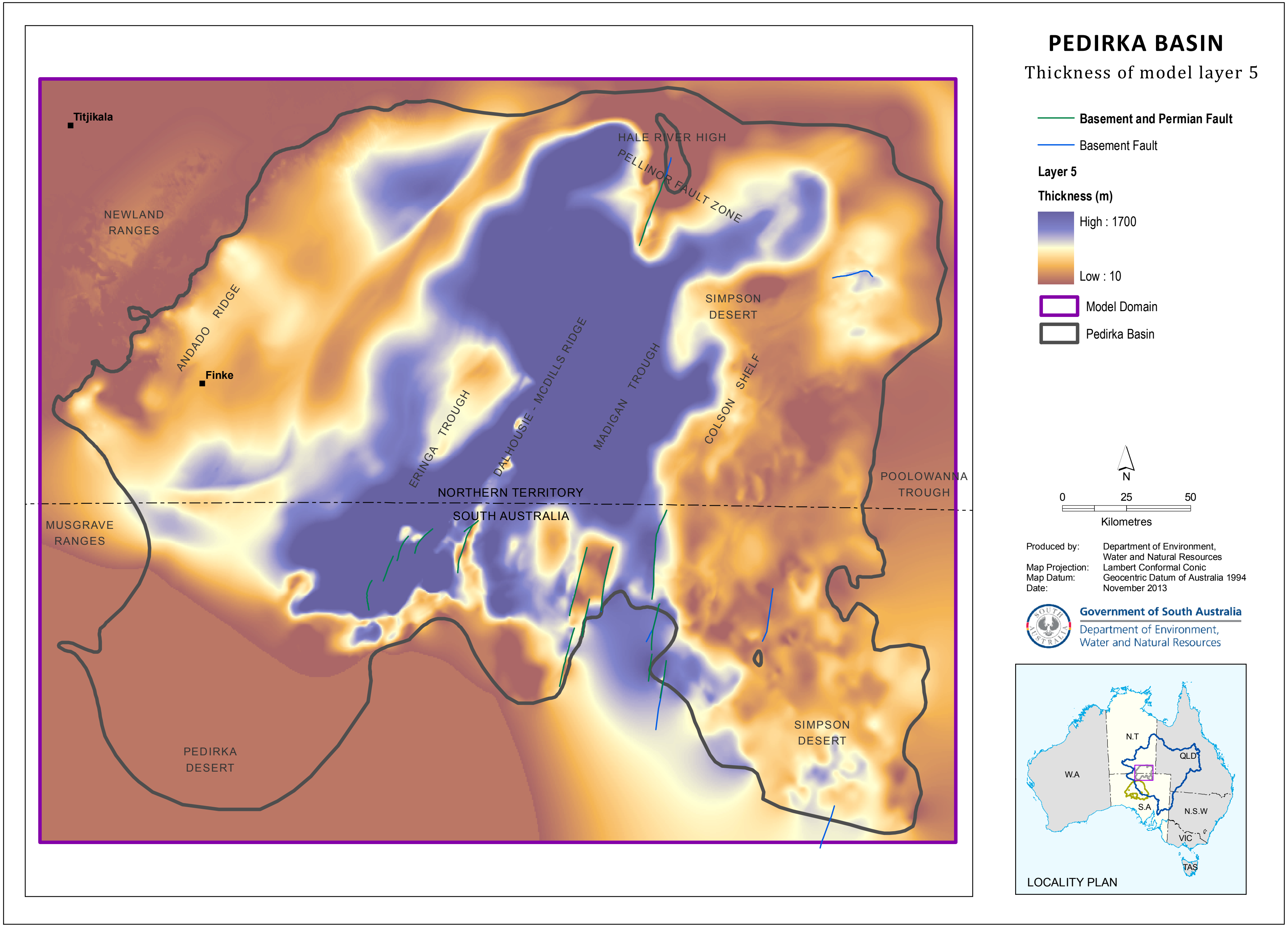

Figure 3.11: Thickness (m) of model layer 5

3.6 Model hydraulic parameters

Model hydraulic parameters are based on a range of aquifer and aquitard hydraulic parameters sourced from published literature, permeability data and a single pump test and current knowledge in other areas. The adopted aquifer and aquitard hydraulic parameters are given in Table 3-2 along with a range of estimates obtained from available data. The spatial distribution within each model layer is shown in Figure 3.12 to Figure 3.15.

Table 3-2 Adopted aquifer and aquitard hydraulic parameters and ranges in field estimates

Hydro-geological unit	Model layer	Modelled hydraulic parameters			Estimates of hydraulic parameters		Data sources
		Kh (m/d)	Kv (m/d)	Ss (-/m)	Kh (m/d)	S (-)	
J Aquifer	2	7 (20 in a small zone*)	0.7 - 2	1×10^{-5}	Lower value 0.1 to 1.6 ; higher value 7 to 20	7×10^{-6} to 7×10^{-3}	Keppel et al. (2013)
Triassic	3	1×10^{-7}	1×10^{-7}	1×10^{-5}	No data	No data	
Purni Formation	4	0.5	0.05	1×10^{-5}	1.7×10^{-4} -2.44	No data	Wohling et al. (2013)
Crown Point Formation	5	1 (20 in a small zone*)	0.1 - 2	1×10^{-5}	0.08 - 1.66	No data	Wohling et al. (2013)
Basement	6	0.01	0.001	1×10^{-5}	No data	No data	

*Finke River recharge region

The regional hydraulic conductivity of the J aquifer of 7 m/d is based on a representative value from literature review (Keppel et al., 2013). The vertical hydraulic conductivity of the J aquifer is assumed to be 1/10th of the horizontal hydraulic conductivity. There are no estimates of the hydraulic properties of the Triassic, and yet it is considered critical to understanding the connectivity between the J aquifer and Permian aquifer.

Regional modelled hydraulic conductivity of the Purni Formation and Crown Point Formation are estimated from a mid-range derived hydraulic conductivities from permeability measurements. Where outcropping Crown Point Formation intersects the Finke River, the hydraulic conductivity is assumed to be higher locally and assigned the same value as J aquifer. The vertical hydraulic conductivity of the Permian aquifers is assumed to be 1/10th of the horizontal hydraulic conductivity. There are no available estimates of the hydraulic properties of basement.

Storativity estimates are available for the J aquifer however there are no estimates available for the remaining units. A uniform value of specific storage of 10^{-5} /m has been adopted for all layers, on the basis of an average value from J aquifer and text book value for general confined aquifer.

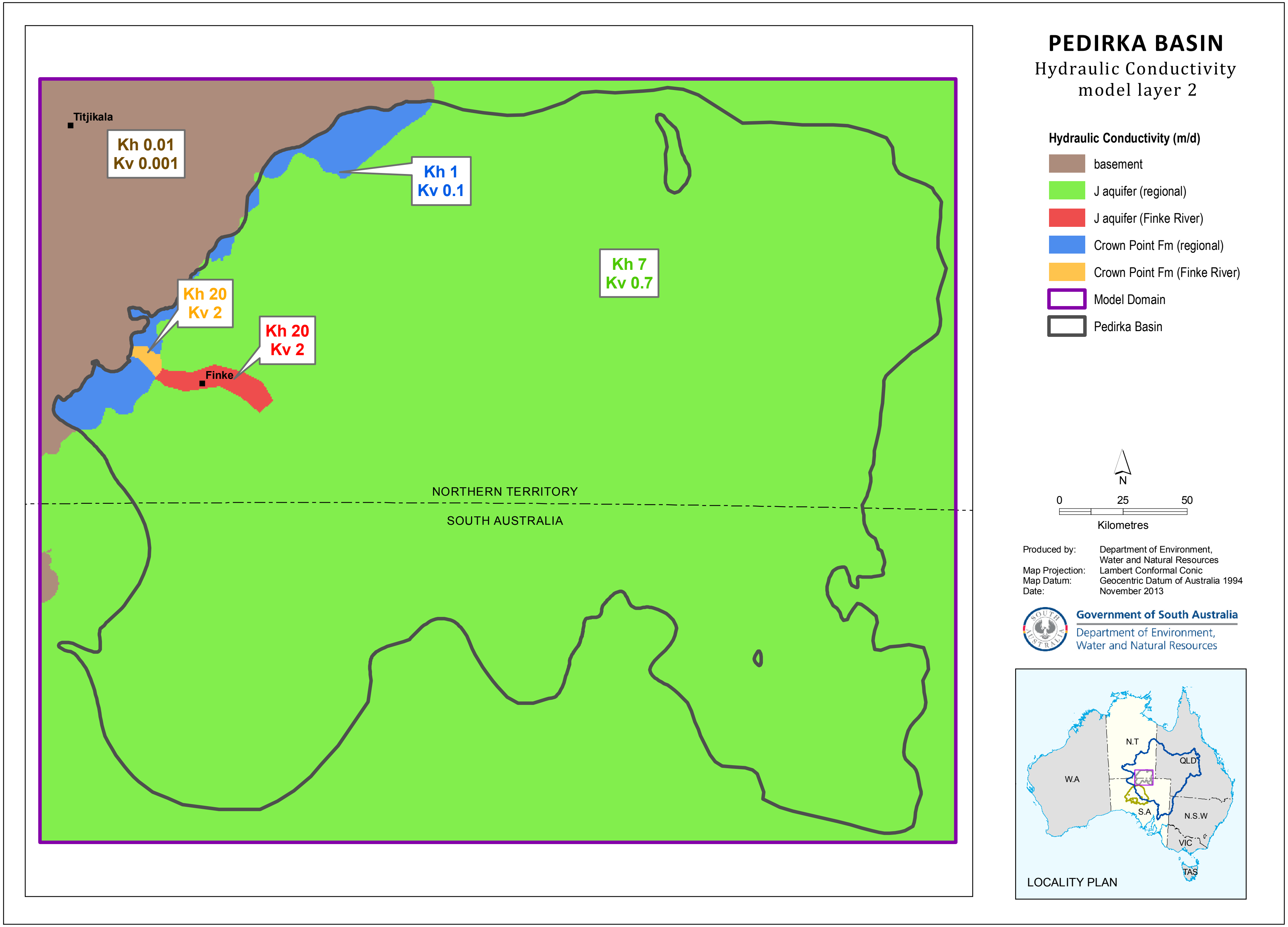

Figure 3.12: Model hydraulic conductivity for layer 2 (m/d)

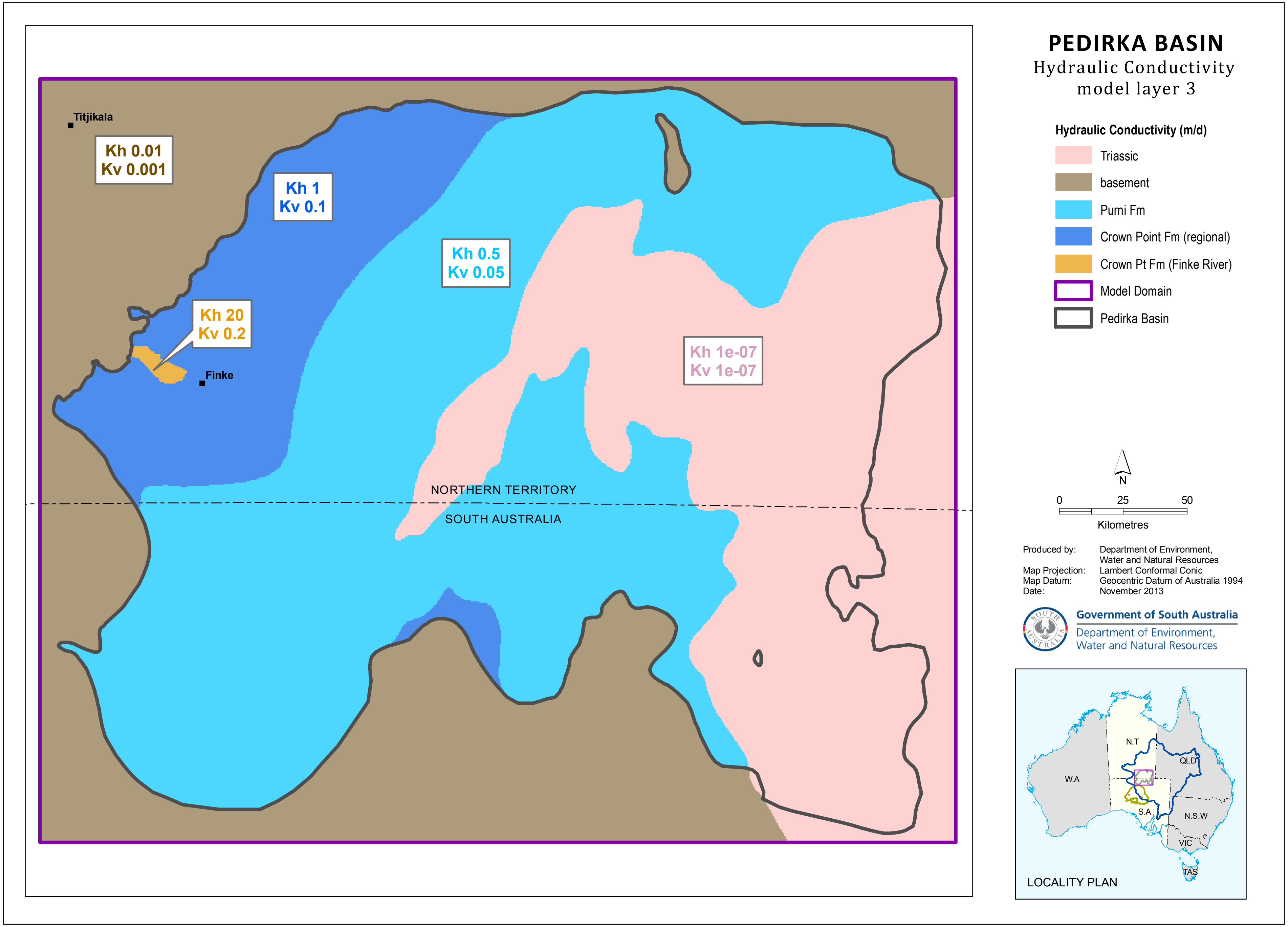

Figure 3.13: Model hydraulic conductivity for layer 3 (m/d)

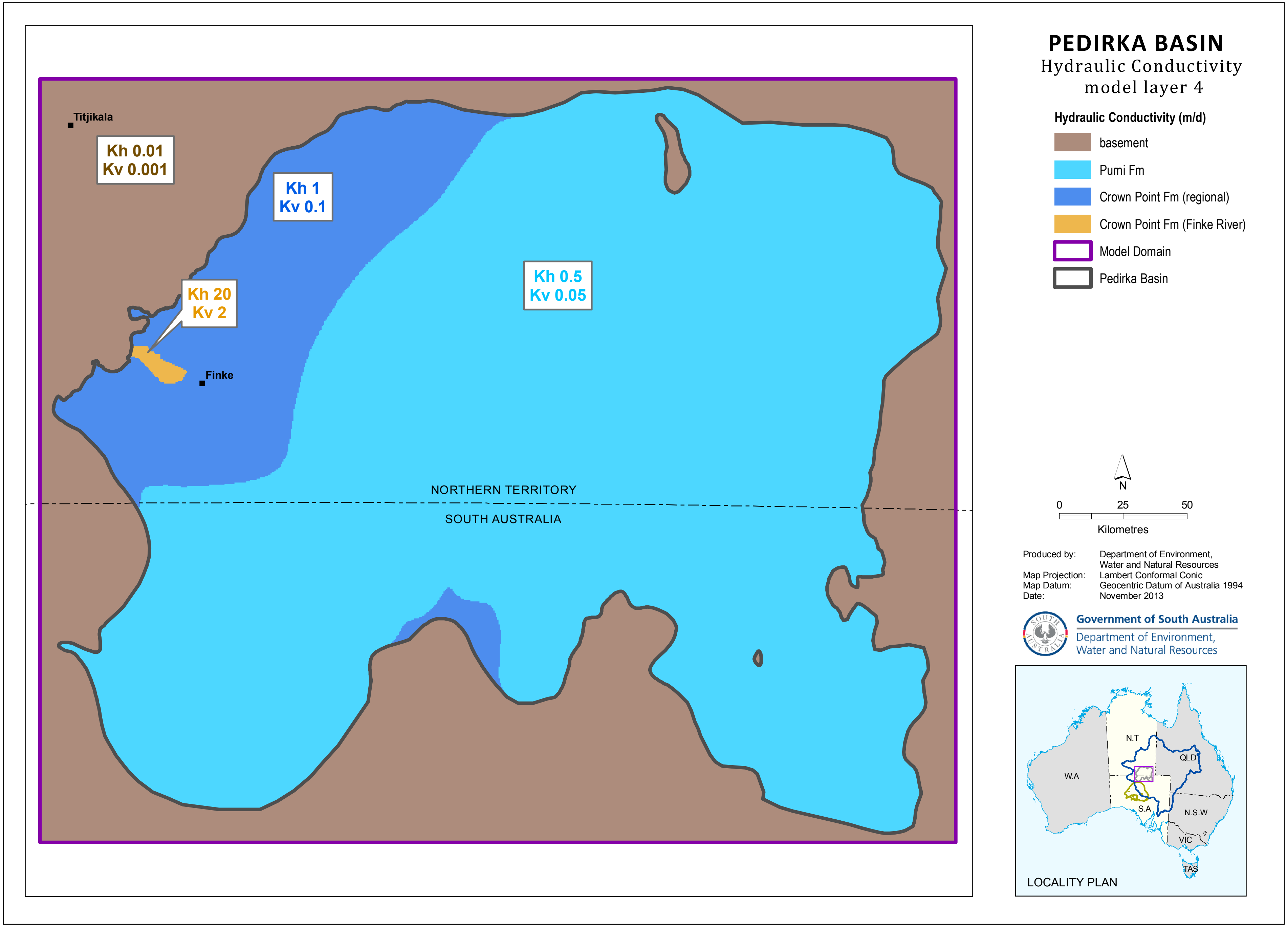

Figure 3.14: Model hydraulic conductivity for layer 4 (m/d)

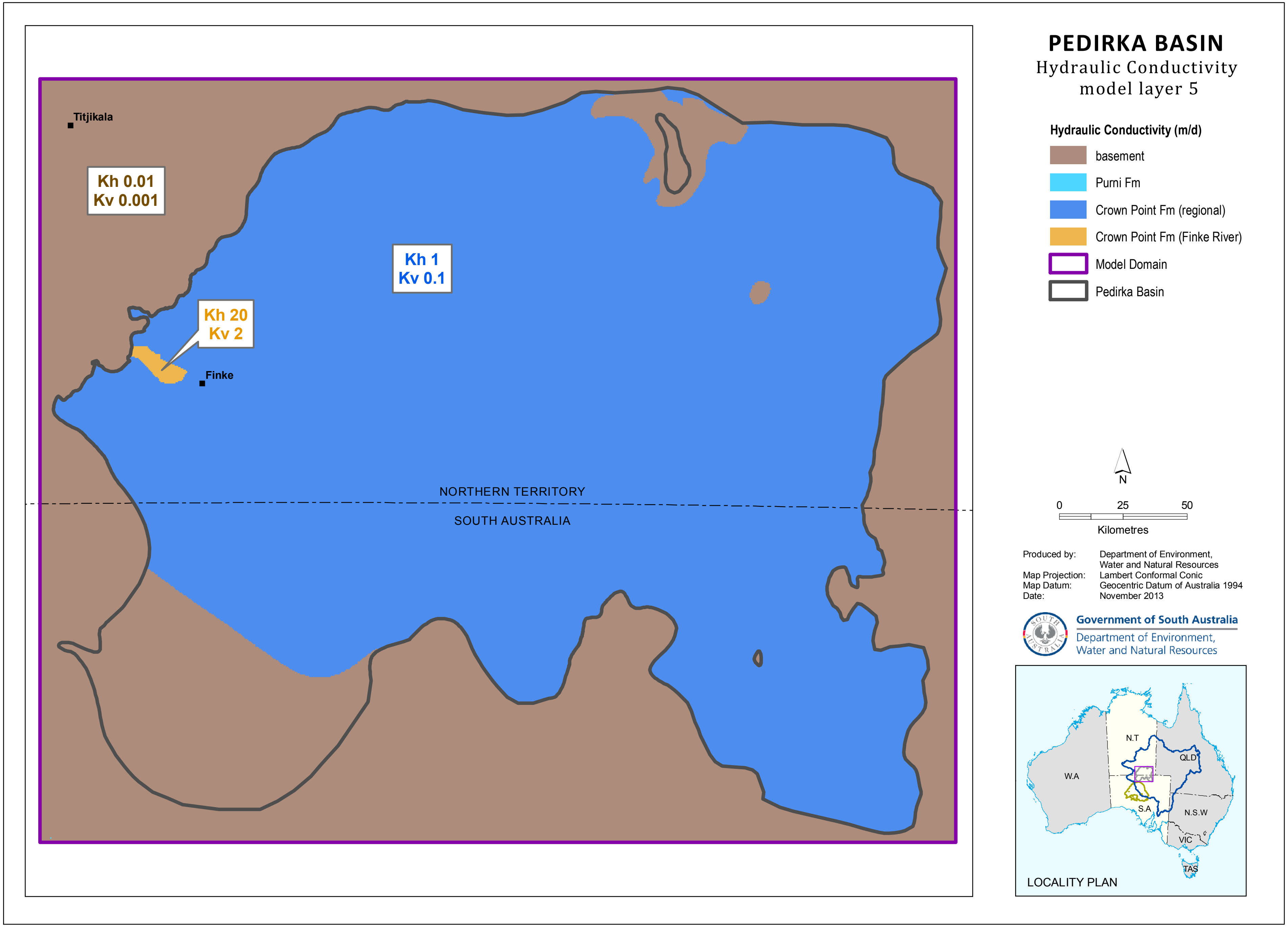

Figure 3.15: Model hydraulic conductivity for layer 5 (m/d)

3.7 Model boundaries

This section describes boundary conditions representing regional flow into and out of the model domain. Groundwater evapotranspiration (ET) and groundwater pumping are excluded from the model due to limited data availability, and assuming minimal impact on major aquifers and minimal impact on overall water balance of the basin. The Dalhousie Springs are also excluded from the model. The source and contribution of discharge to the springs is not known with certainty, as the springs are located outside of the basin and their linkage to the Permian aquifers is poorly understood.

3.7.1 Regional Flow

Regional lateral inflow and outflow of the modelled region is simulated using general head-boundary (head-dependent flow) cells along the edges of the model domain where the aquifer is saturated and groundwater flow direction is inferred from water level contours. Areas where water-level contours are approximately perpendicular to the boundary are assigned as no-flow boundaries.

The general head boundary conditions assigned for model Layer 2 (J aquifer) are shown in Figure 3.16. These represent regional lateral inflow from the north through the J aquifer and regional lateral outflow via the J aquifer along the southern boundary. The head assigned along the northern boundary (190 m AHD) and southern boundary (130 m AHD) are based on water level contours for the J aquifer as shown in Figure 2.6.

The general head boundary conditions assigned for model Layers 4 to 6 represent lateral flow into and out of the model through basement (Figure 3.17). The head value assigned to the southern boundary condition is the same as the head in Layer 2 (130 m AHD) as there are no reliable measurements for the Permian units close to this boundary (see Section 2.4.3.3).

The head values assigned at the regional boundaries do not change over time. The conductance assigned to the general head cells is 1000 m^2/d.

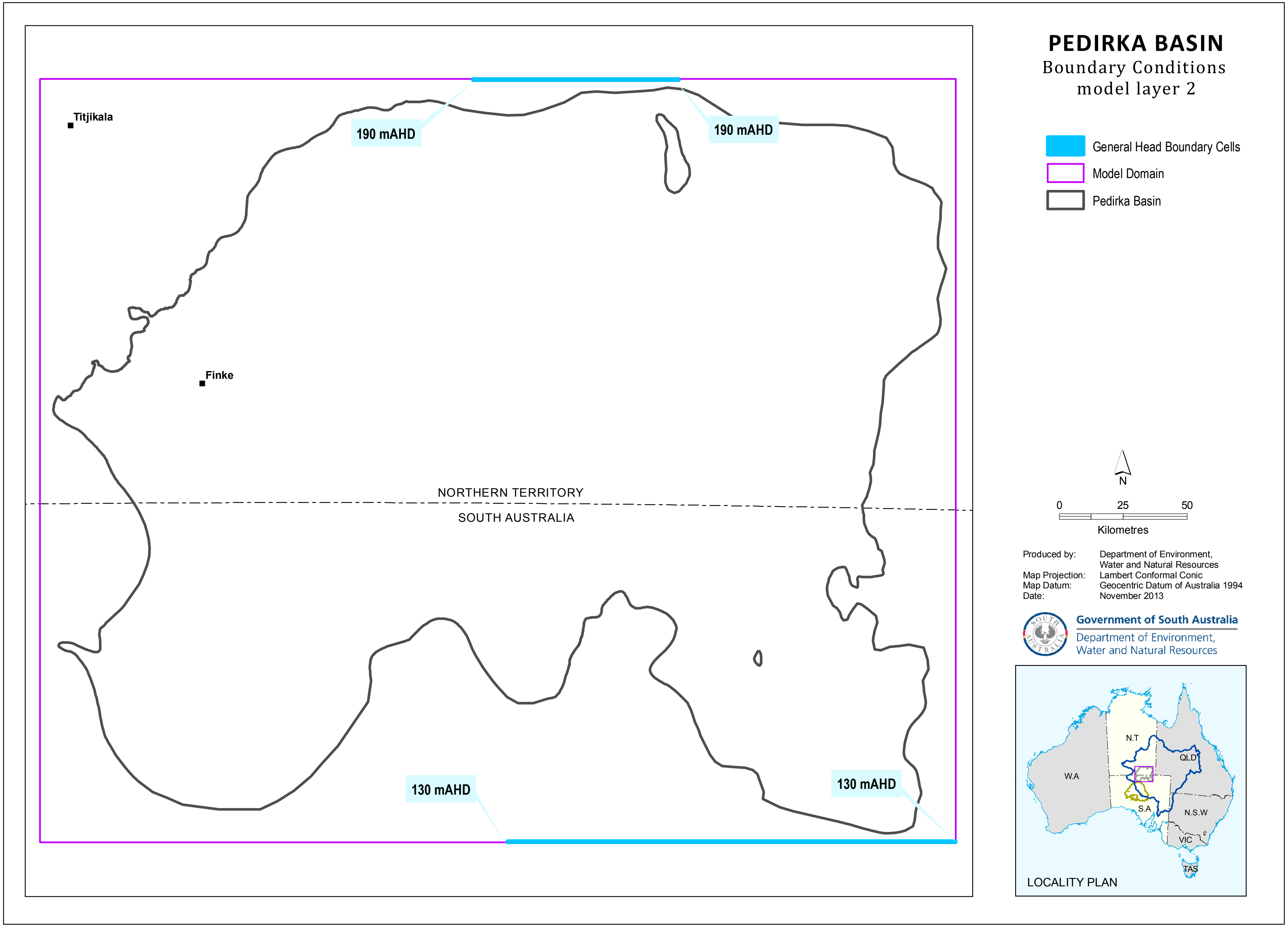

Figure 3.16: Boundary conditions for model layer 2 (m AHD)

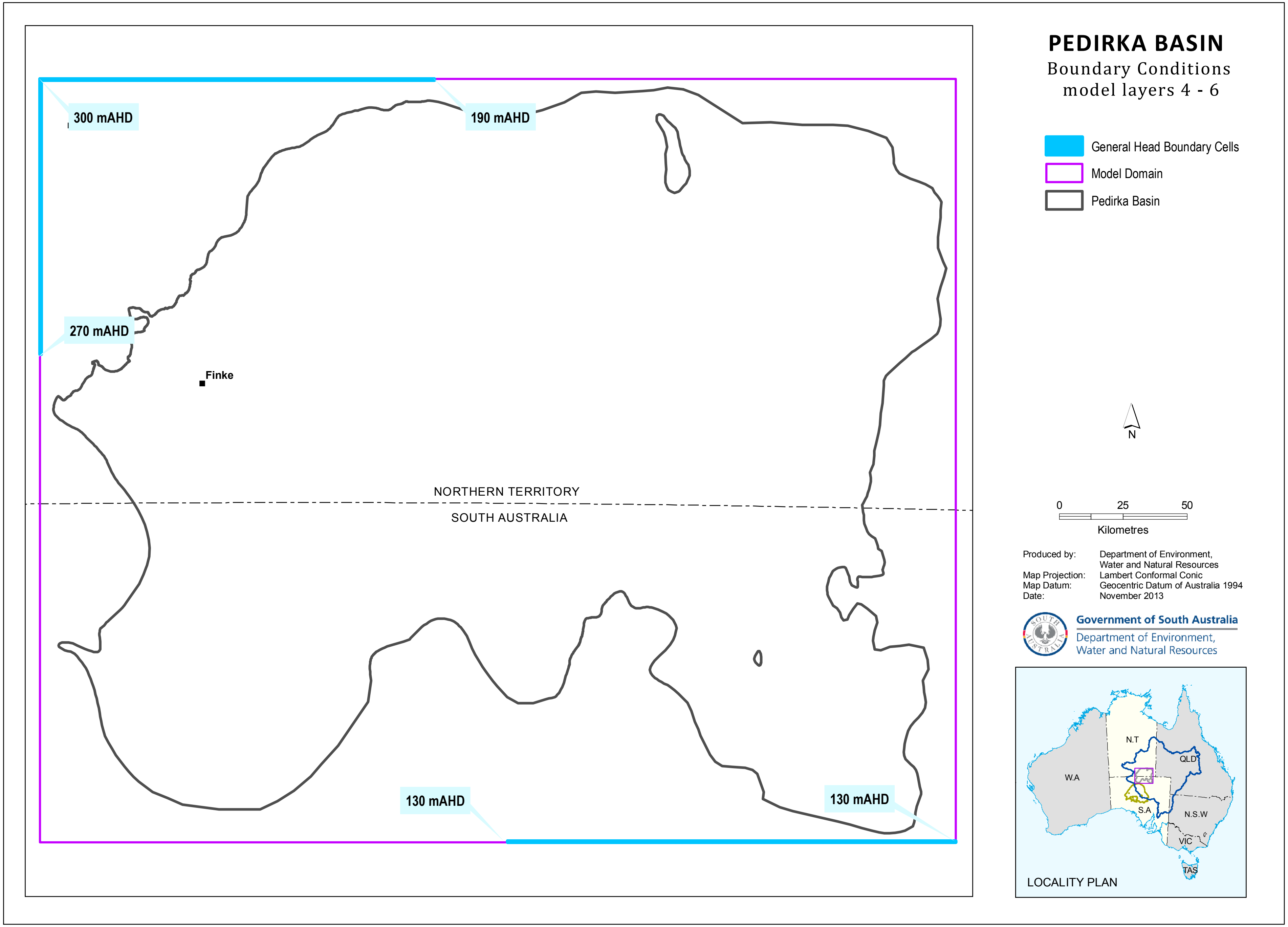

Figure 3.17: Boundary conditions for model layers 4 - 6 (m AHD)

3.8 Model recharge

Mechanisms for recharge to the Pedirka Basin include diffuse recharge and recharge from surface water features such as rivers and creeks. Recharge features are represented in the model using the MODFLOW Recharge (RCH) Package. Recharge is applied to the highest active model layer.

3.8.1 Diffuse recharge

A hypothetical trend in palaeorecharge over a period of 100 000 years is simulated (Figure 3.18). The initial diffuse recharge in the steady state model, representing a condition in the past, is 5 mm/y which is about 1% rainfall (500 mm/y). It assumes that greater rates of diffuse recharge would have occurred in the past, and that rates have been linearly declining over the recent climate cycle. The diffuse recharge rate of 5 mm/y was applied in steady state model, and the rate declines 1 mm every 1000 years for the first 4000 years and declines to 0.1 after 5000 years, This modern-day recharge rate of 0.1 mm/y persists through the transient model run until model simulation time step 100 000 (years).

The model estimates how the system changed in past and how long the system takes to reach equilibrium over this long period of drying conditions (e.g. recharge rate ~0.1 mm/y).

There is no data available to indicate the area over which diffuse recharge occurs or has occurred in the past. Current knowledge and information indicate that diffuse recharge to the Permian aquifers most likely occurs only along the north-west region of the Pedirka Basin, coinciding with the area where the J aquifer is currently unsaturated or absent. Distribution of this zone of diffuse recharge is presented in Figure 3.19.

3.8.2 Recharge from surface water features

There are number of surface water features located within the model extent (Figure 2.1). There is limited data available to suggest how those surface water features recharge the Permian aquifer systems. Current information and data suggest that Finke River and Goyder Creek most likely are the main surface water features recharging the aquifer systems. It is assumed that this occurs where the J aquifer and Permian aquifers outcrop along the north-west margin of the basin.

The model recharge from Finke River and Goyder Creek is unchanged over the model simulation period of 100 000 years. This simple representation of Finke River and Goyder Creek is considered reasonable given the aims of the model. In reality, flow regimes vary and higher flows potentially occurred in the past due to wetter climate therefore leading to higher recharge rates.

Model recharge zones for the streams are shown in Figure 3.19. Based on information from Love et al. (2013a), the modelled rate of the recharge from Finke River along J aquifer outcropping locations is assumed as 369 mm/y, occurring over a model recharge zone of 18 km^2. A rate of 369 mm/y is assumed for recharge from Finke River along Crown Point Formation aquifer outcropping locations. This rate is slightly less than the range in field estimates to account for model cell size.

The modelled recharge volume for Goyder Creek is unknown and assumed to be roughly an order of magnitude less than the Finke River recharge volume. A recharge rate of 30 mm/y has been assumed, along J aquifer and Crown Point Formation aquifer outcropping locations, which was based on an assumption of 10% of Finke River surface water flow data.

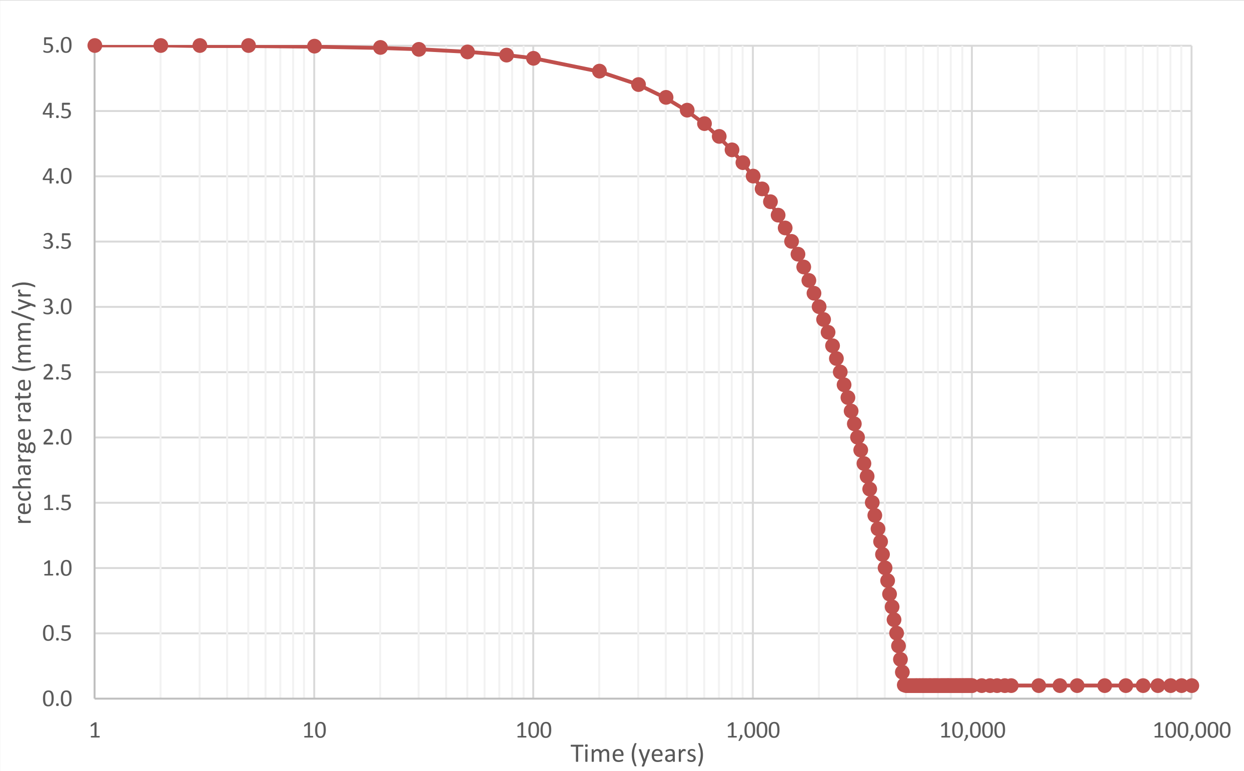

Figure 3.18 Modelled trend in diffuse recharge rate

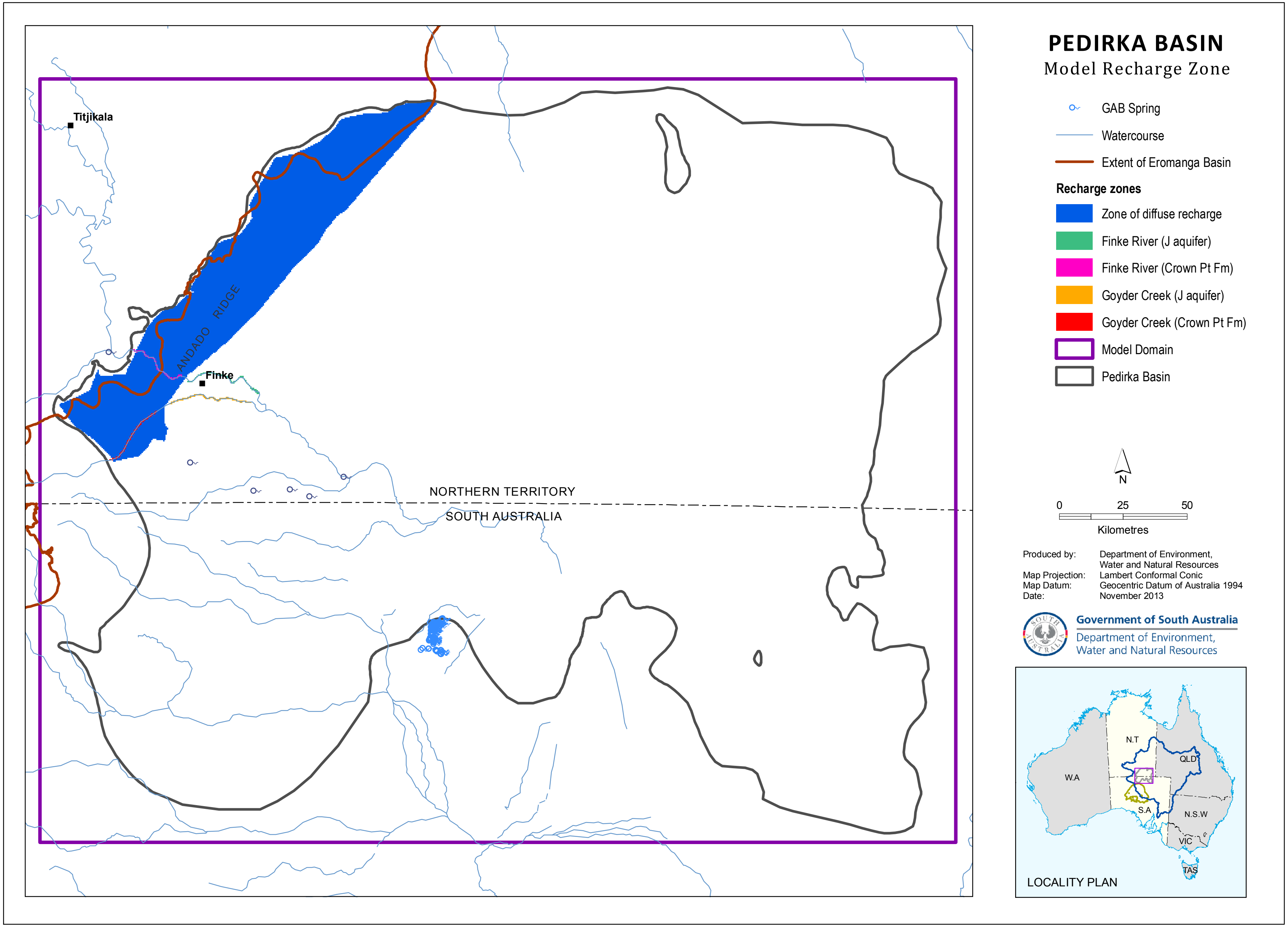

Figure 3.19: Model recharge zones

4 Model calibration and confirmation

4.1 Model calibration

Detailed calibration was not conducted because of limited monitoring data and information available to constrain the model, more specifically water level measurements, flux estimates and reliable aquifer properties. A process of model confirmation was conducted to ensure the model simulates the system and model results are similar to the measured data and current understanding. Based on existing data, information and objectives of the modelling exercise and according to Australia Groundwater Modelling Guideline, the model was developed as a regional-scale, elementary Class 1 model (Barnett et al., 2012). It is considered fit for purpose for the current project.

4.2 Model confirmation

The steady state model simulates long-term average conditions which assume higher diffuse recharge (5 mm/y) occurred in the past. Model confirmation process was conducted to ensure that the modelled steady state water level is higher than current measurements and has similar flow directions as per the latest potentiometric surface.

The steady state model water level result is used as the initial conditions for the transient simulation, which include simulation of the current groundwater conditions. The current conditions from transient model was confirmed by:

- Modelled water level, measured water level and flow direction
- Timelag between recharge and discharge is similar to current understanding (Love et al., 2013a)
- Modelled water level decline is similar to estimations in the western GAB where water levels are declining by approximately 3 cm per 100 years (Love et al., 2013a).

4.2.1 Water level

Figure 4.1 displays the modelled water-level contours for Layer 2 (J aquifer) and Layer 5 (Crown Point aquifer) in steady state, which represents the long term average conditions with higher diffuse recharge (5 mm/y) which has been assumed to have occurred in past. The modelled water level is slightly higher than the observed water level and flow direction compares reasonably well (Figure 2.8).

Modelled flow occurs from the recharge area along the north-west margin of the basin toward the south-east, with lateral inflow occurring from the north. A maximum modelled head of 210 m AHD is observed along the north-west margin of the basin. Close to Finke River and Goyder Creek, groundwater levels are enhanced by local recharge (Figure 4.1).

A negligible head difference between the Permian aquifer and J aquifer is indicated where the Triassic is absent. Where the Triassic is present and is relatively thick, the vertical head gradient between the J aquifer and Permian aquifer is up to +3 m (upward).

Results from the transient model simulation indicate between time step 9100 and 9200 (a period of 100 years) show a decline in Layer 2 (J aquifer) is between 5 mm and 50 mm across the basin (Figure 4.2). This compares well with the approximation (~30 mm/100 year given by Love et al, 2013a).

In the Pedirka Basin area, if we postulate that model simulation time step 9200 (year) represents the current condition, then the modelled water level matches well with observed water level contours in most areas in the main aquifers. In a small area along the north-west margin, the modelled water level is lower than interpreted level by up to 60 m in the Permian aquifer (Figure 4.3). This may be a consequence of data limitation, complication of real conditions (geology and hydrogeology) and model simplification within the area.

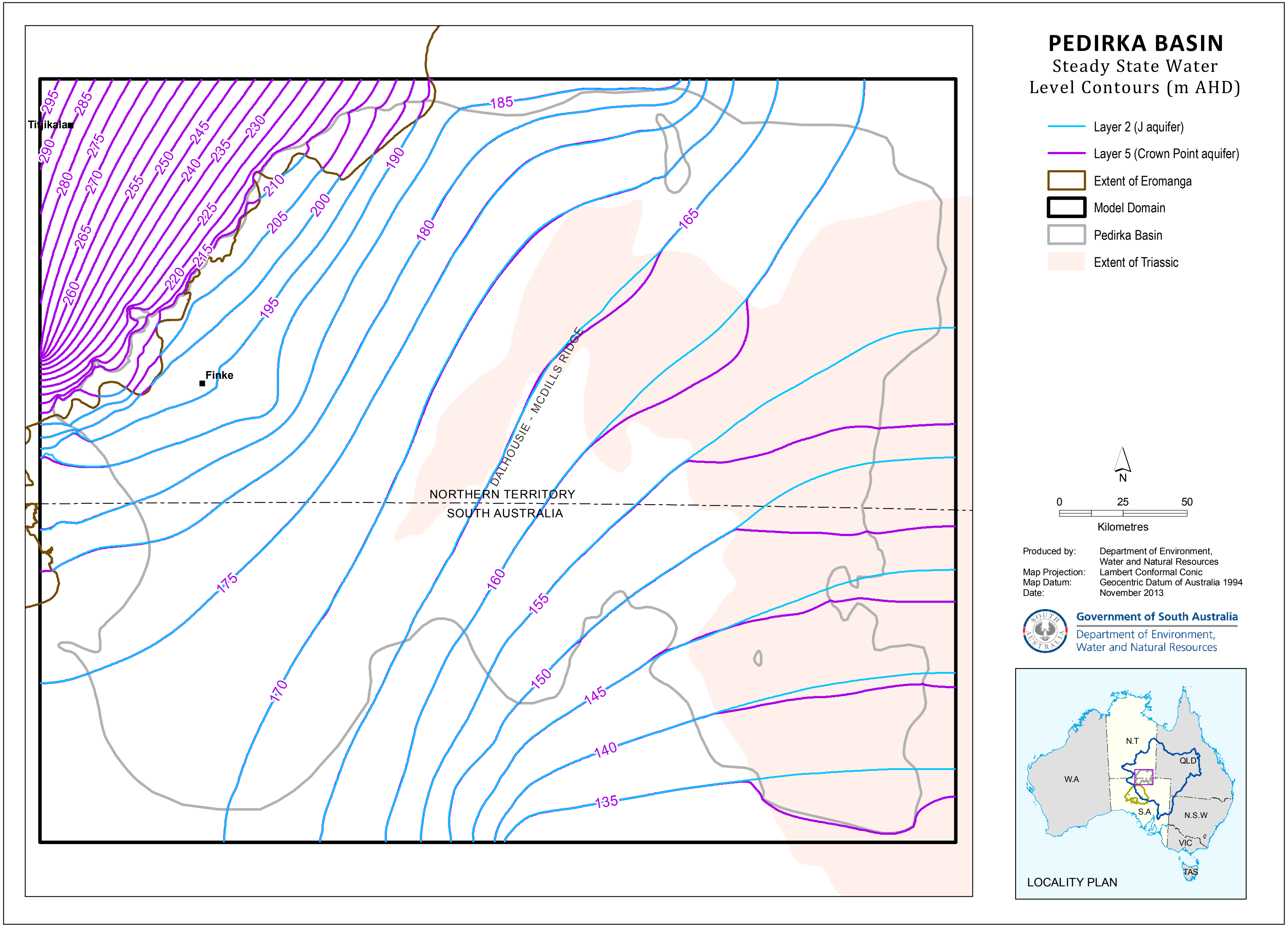

Figure 4.1: Steady state water level contours (m AHD)

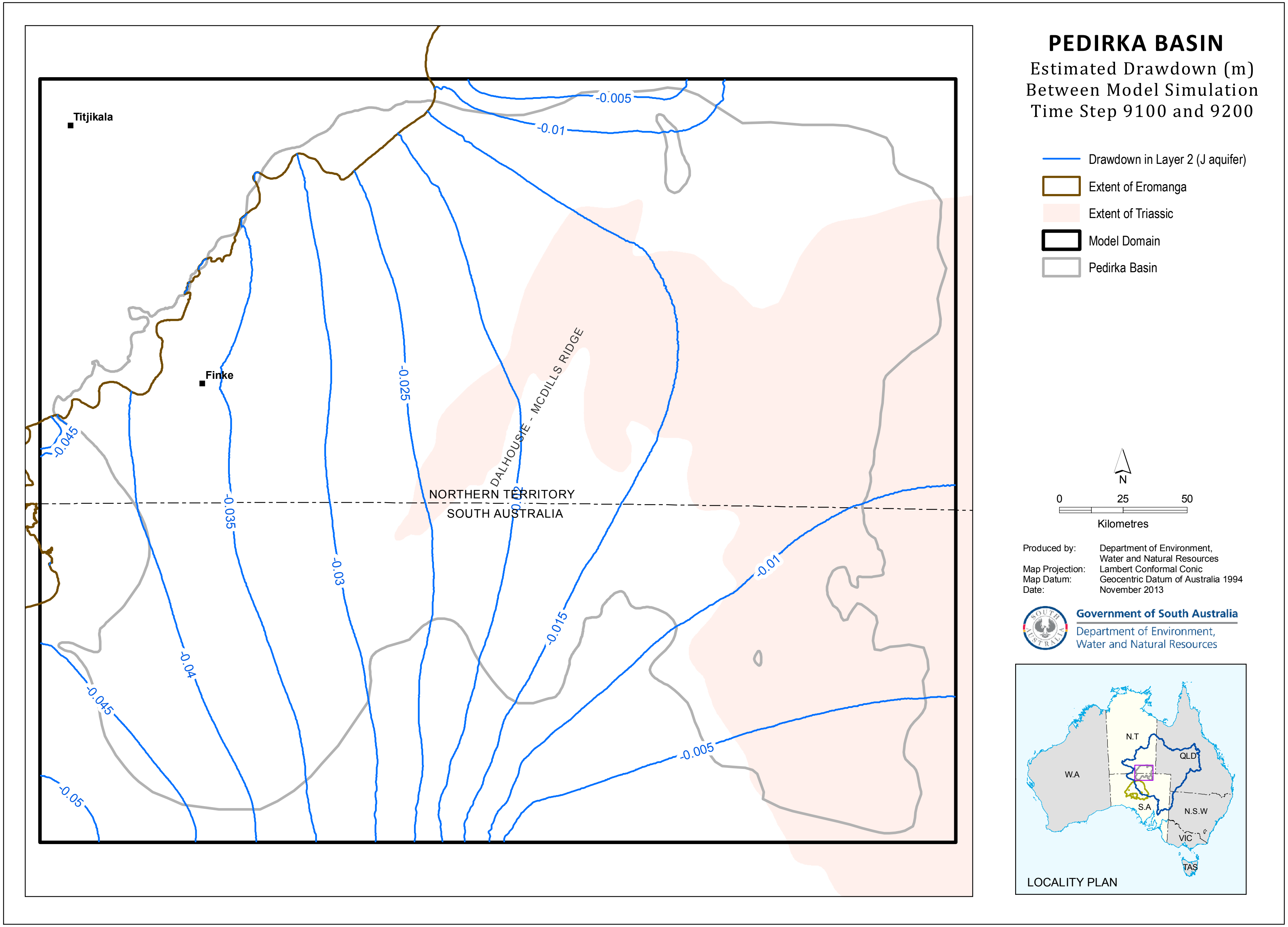

Figure 4.2: Estimated drawdown (m) between model simulation time step 9100 (year) and 9200 (year)

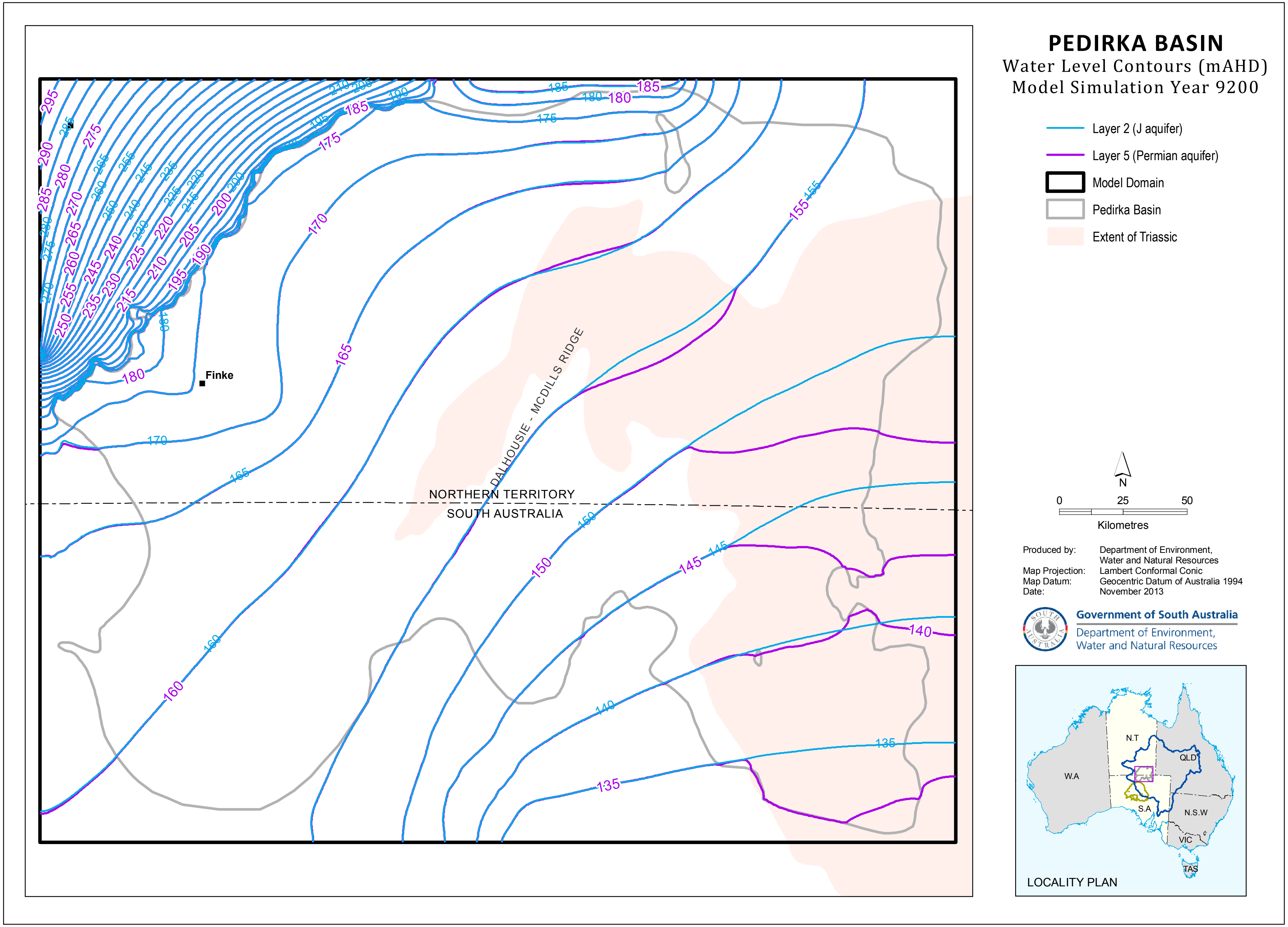

Figure 4.3: Water level contours (m AHD) - model simulation year 9200

4.2.2 Water balance

The model water balance provides the primary sources of inflows and outflows to the system. Figure 4.4 and Figure 4.5 show the mass balance from steady state model (past) and from model simulation time step 9200 (current). The graphs are annotated with the relative percentages of inflows and outflows to the model.

4.2.2.1 STEADY STATE MODEL WATER BALANCE (PAST)

From steady state model, groundwater total inflow into the model domain is estimated at approximately 156 ML/d (Figure 4.4). This includes recharge of 66% (41% is diffuse recharge and 25% is recharge from streams) and 34% lateral inflow (through the General Head Boundary (GHB) – mostly via J aquifer). Approximately 70% of the diffuse recharge volume recharges the J aquifer and 30% recharges the Permian aquifer, where the J aquifer is unsaturated or where Permian aquifer outcrops.

Total discharge occurs laterally through aquifers on the south-east boundary (GHB). Lateral outflow via the J aquifer comprises 98% of total outflow, indicating that most recharge to the Permian aquifer discharges vertically to the J aquifer.

4.2.2.2 TRANSIENT MODEL WATER BALANCE (CURRENT)

At model simulation time step 9200 (year), total inflow (recharge and lateral inflow) is estimated at 116 ML/d, a reduction of approximately 25% from the past due to reduced diffuse (rainfall) recharge (Figure 4.5). Proportion of the diffuse recharge to the basin has reduced to 1% of total inflows from 41% in steady state. Approximately 52% of all inflows occur laterally to the J aquifer.

Total outflow (discharge) is estimated at 119 ML/d. Discharge exceeds total recharge by approximately 3 ML/d, demonstrating that the system is still equilibrating to the decline in diffused recharge.

The model results show that the equilibrium lag time between recharge and discharge (lateral outflow) is likely be several thousand years or longer. The model result indicates that, following the recharge volume stabilising around time step 5000 (year), there is potentially an additional 7000 years for discharge to reach equilibrium (Figure 4.6). It is emphasized that the estimated water balance for the basin is indicative only and although the model has been developed using the best available hydrogeological data, there are key knowledge gaps and limited data available to constrain the accuracy of model results.

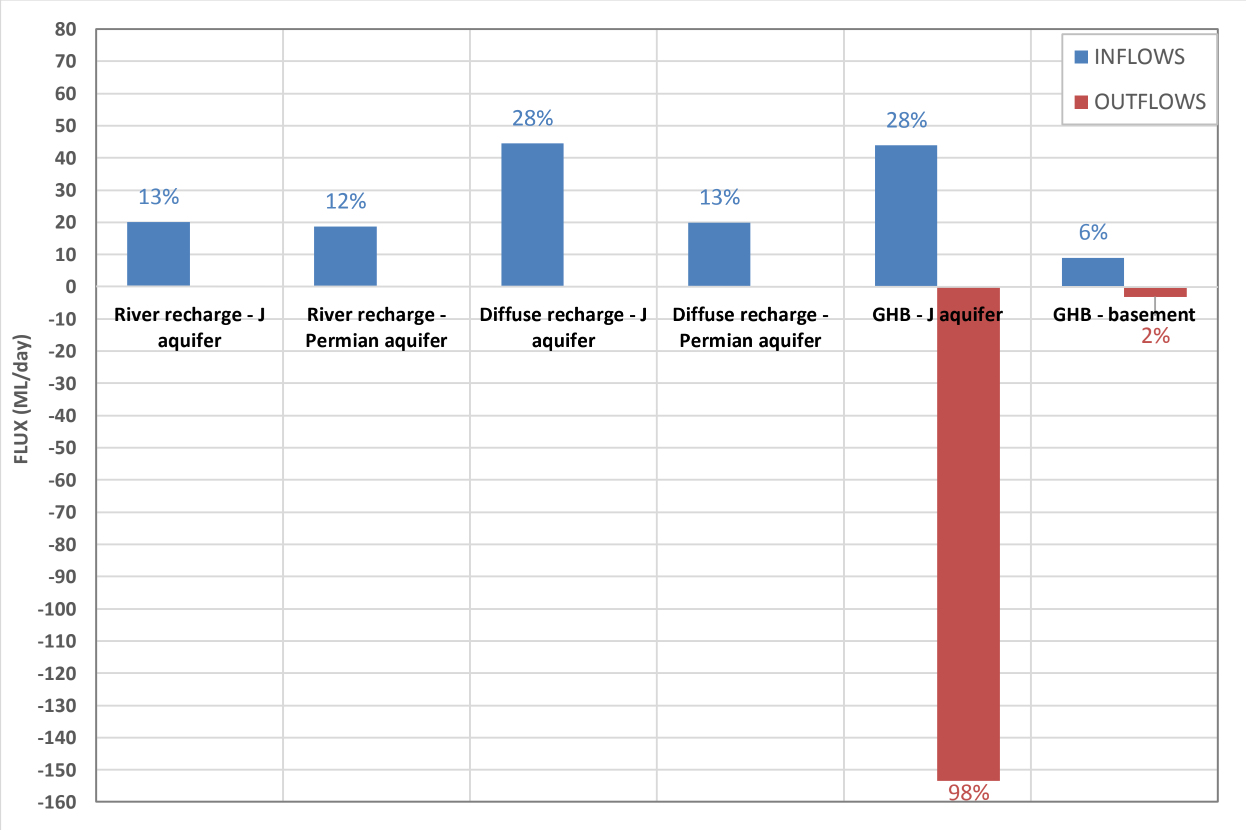

Figure 4.4 Model water balance – steady state

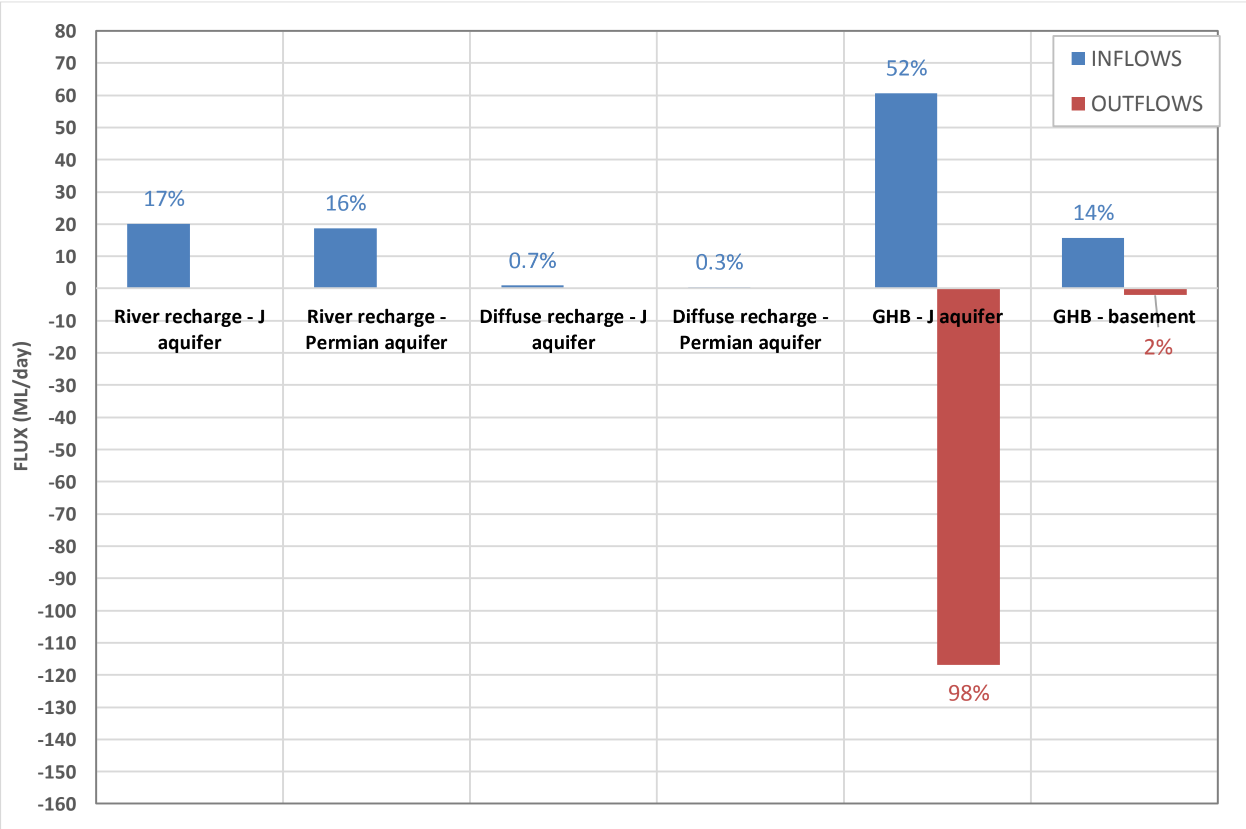

Figure 4.5 Model water balance – simulation time step 9200

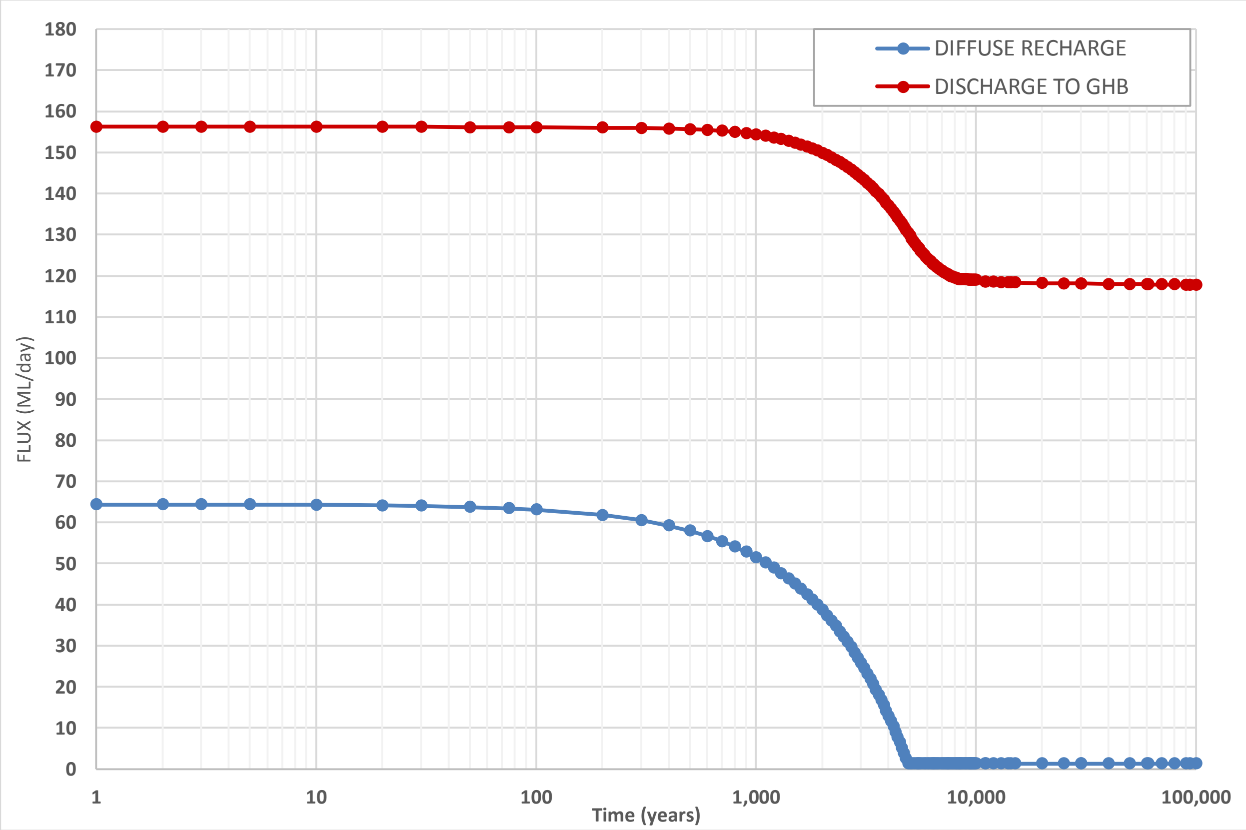

Figure 4.6 Diffuse recharge and lateral outflow (total discharge) to southern boundary

5 Sensitivity and uncertainty analysis

Sensitivity analysis is a procedure for quantifying the impact of an incremental variation in aquifer hydraulic parameters or stresses on modelled responses (Middlemis et al., 2000). A manual sensitivity analysis is performed, which requires changing a single model parameter, re-running the model to obtain a new set of predicted heads and fluxes and observing the effect of the change. The emphasis is on determining how sensitive the model is to each parameter (Barnett et al., 2012).

There is considerable uncertainty in a number of key parameters used in this model due to lack of field estimates. The aim of this analysis is to evaluate the sensitivity of the model to several key parameters, only varying these parameters within reasonable limits on the basis of hydrogeological knowledge. The sensitivity results are presented in terms of head, model water balance and lag time between recharge and discharge.

One sensitivity test was conducted to test stresses on modelled responses. The test was to gain a general understanding of how the model reacts to a potential impact, on dewatering at a hypothetical mine location. The result is examined in terms of impact of drawdown on a regional scale.

An uncertainty analysis was conducted to evaluate the potential numerical error associated impact on model results, related to define all aquifers as confined aquifer in whole model domain.

5.1 Sensitivity to parameters

5.1.1 Parameters and values

In keeping with recommendations from the Australian Groundwater Modelling Guidelines (Barnet et al., 2012), each parameter is adjusted by an amount commensurate with its likely range. As the Pedirka Basin is regarded as a data poor area it is difficult to determine likely ranges in parameters. Parameters were varied in a range documented in literature.

During the tests, each parameter was varied individually, except the conductivity of Purni Formation and Crown Point Formation which were varied together. Only the regional value for hydraulic conductivity was varied (locally high conductivity around Finke River is unchanged).

For the purposes of reporting, sensitivity tests results are compared with to the simulation model (reported in Section 4) which named as “base case”. Table 5-1 gives the values of the parameters in the model (base case) and the values used in the sensitivity tests (“lower value” and “higher value”).

Table 5-1 Sensitivity test parameter values

Parameter	Lower value	Base case value	Higher value
J aquifer Kh, Kv (m/d)	0.7, 0.07	7, 0.7	21, 2.1
Purni Formation Kh, Kv (m/d) ; Crown Point Formation Kh, Kv (m/d)	0.1, 0.01 0.1, 0.01	0.5, 0.05 1, 0.1	2.5, 0.25 5, 0.5
Specific Storage (Ss) (/m)	1×10^{-6}	1×10^{-5}	1×10^{-4}
Diffuse Recharge rate (mm/y)	-	5 to 0.1 over 5000 years	15 to 0.1 over 15 000 years

5.1.2 Sensitivity tests

5.1.2.1 SENSITIVITY TO THE MODELLED WATER LEVEL

To show how the water level changes from the “base case”, difference of the scaled root mean square (SRMS) error between base case and the tests are presented (Figure 5.1). The SRMS value was calculated using modelled water level compared with observed data. Positive values indicate an improved overall fit to the observation data compared to the base case, negative values indicate a worse fit.

To calculate SRMS, modelled water level were extracted from the model at a time when the condition is considered to reflect the current conditions in the basin. All observation data was used in the calculation of SRMS, except three measurements in the south-east of the basin sourced from drill stem tests which were considered less reliable.

The test results of sensitivity to water level are summarised as:

1. **Ss** – Changes in aquifer storage at current condition are relatively small, head changes are minor in subsequent time steps and the system is approaching steady state. Hence the modelled head is similar to the base case for different Ss values, having little effect on SRMS (Figure 5.1).
2. **Kh in J aquifer** – Model results in Figure 5.1 demonstrates the sensitivity of SRMS to the changes of hydraulic conductivity of the J aquifer, and indicate that either increasing (higher value) or decreasing (lower value) Kh will not improve the overall fit between modelled and observed water levels. Most significant changes to modelled head in the steady state model occur along the north-west margin, with tripling Kh lowering the head by approximately 30 m and a tenth Kh increasing the modelled head near Finke River by as much as 130 m (Figure 5.2).
3. **Kh in Permian aquifer** – A hydraulic conductivity of 0.1 m/d for the Permian aquifer may slightly improve SRMS (Figure 5.1). The maximum head along the north-west margin in the steady state model is 240 m AHD, which is a better match to observations (Figure 2.8). Steeper gradients occur where there is recharge directly to the Permian aquifer. Increasing Kh by 5x could lead to a worse overall fit between modelled and observed water levels.

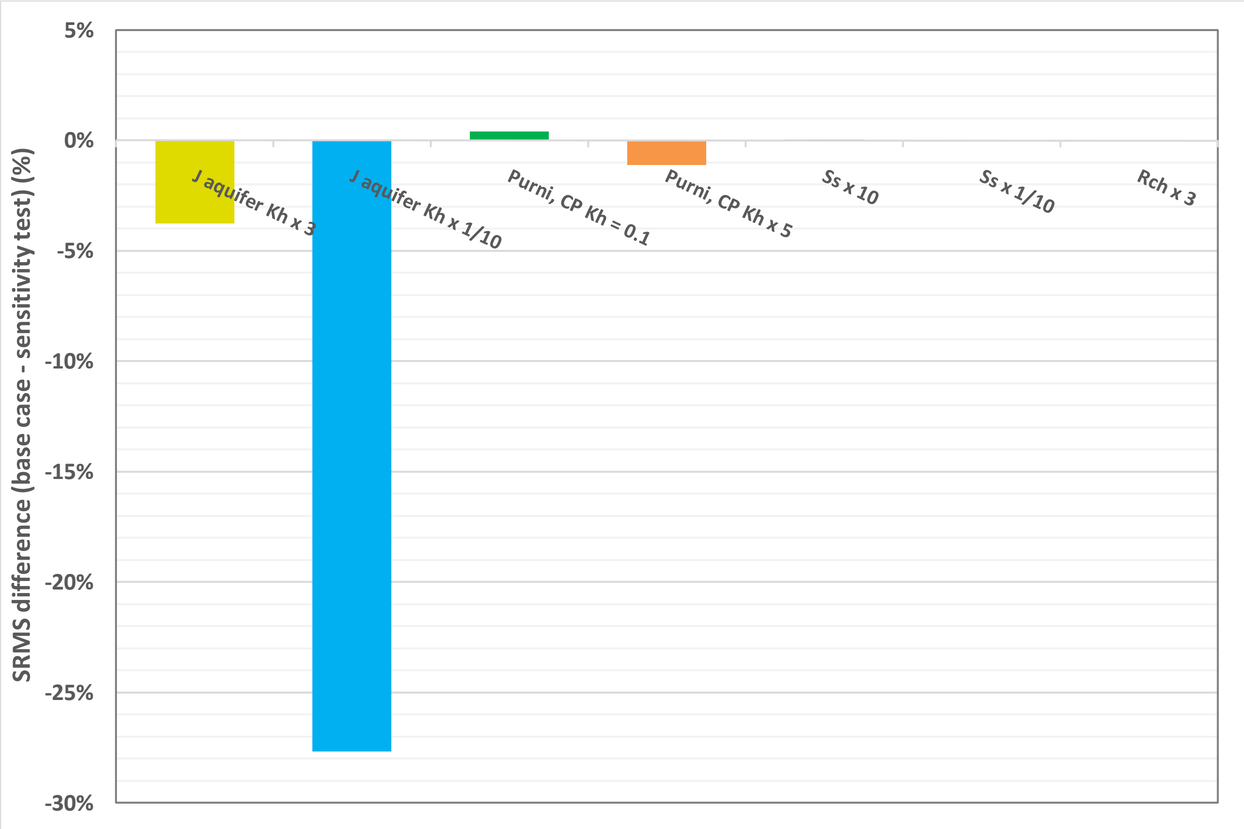

Figure 5.1 Sensitivity test results (SRMS difference to base case)

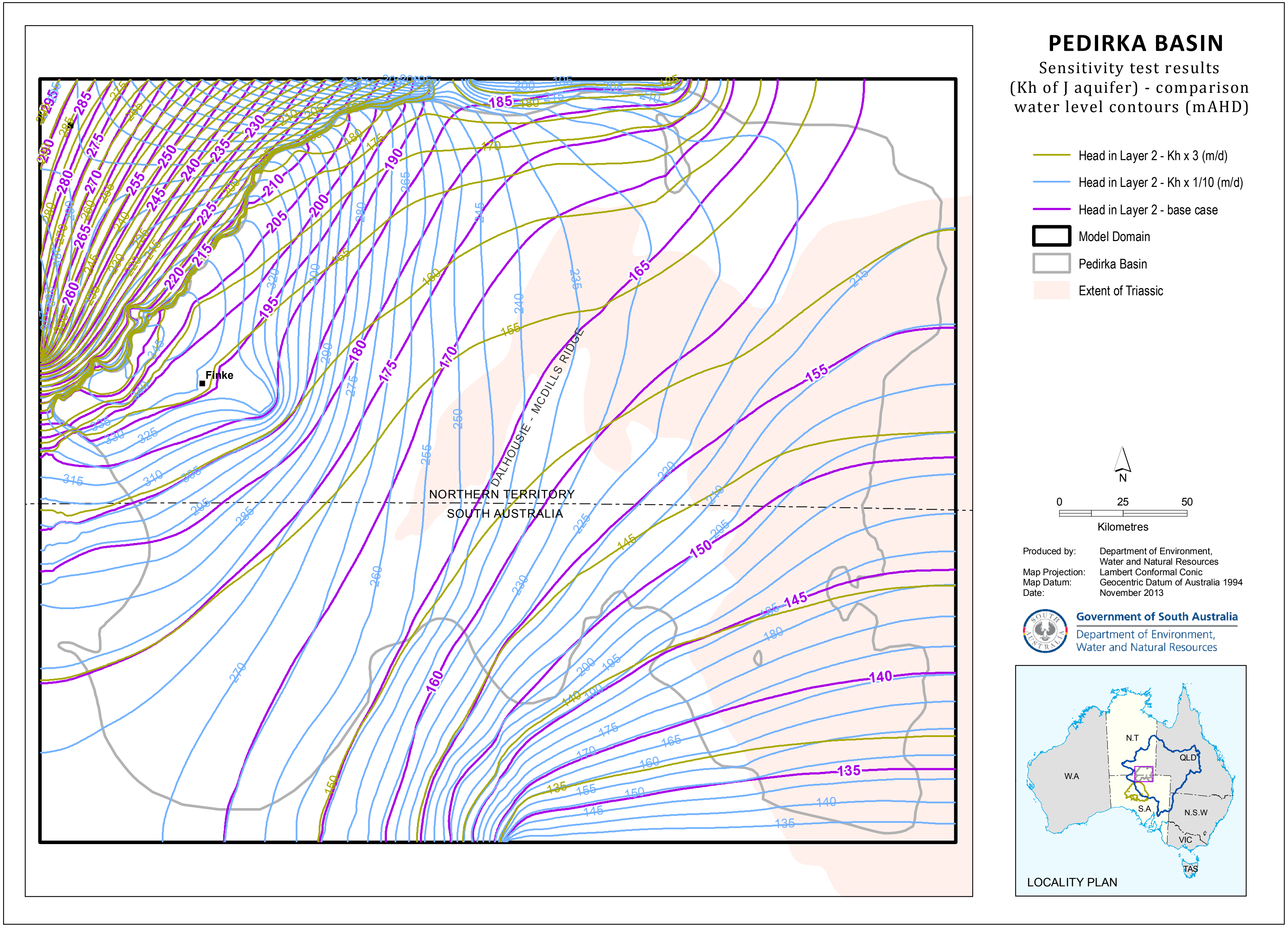

Figure 5.2: Sensitivity test results (Kh of J aquifer) - comparison water level contours (m AHD)

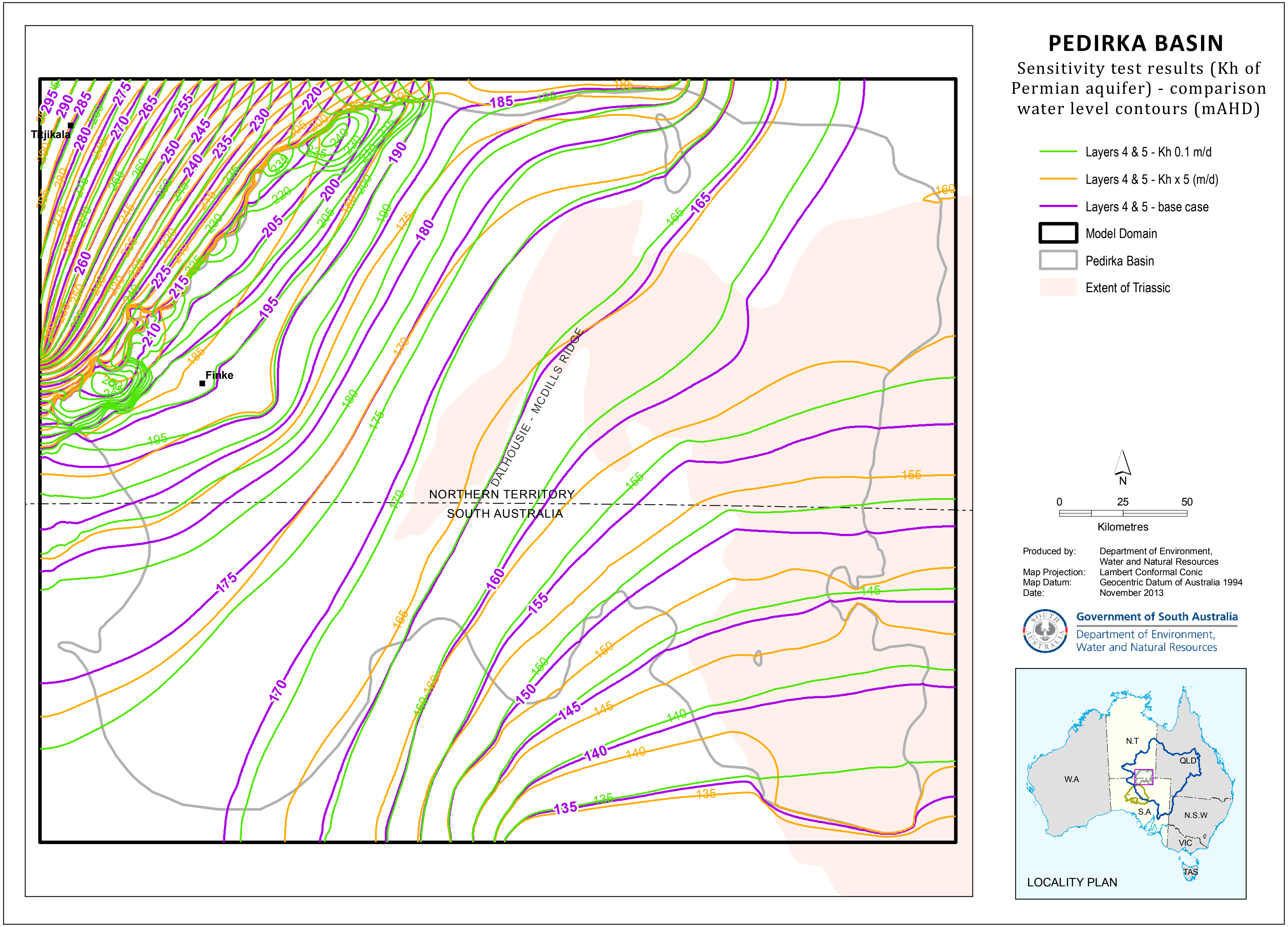

Figure 5.3: Sensitivity test results (Kh of Permian aquifer) - comparison water level contours (m AHD)

5.1.2.2 SENSITIVITY TO MODELLED WATER BALANCE

The results of sensitivity testing in terms of total flow through the model, sources of inflows (recharge) and outflows (discharge) and time lag between recharge and discharge were considered. The results are presented in Table 5-2 and Figure 5.4 to Figure 5.6.

The test results of sensitivity to water balance are summarised as:

- Ss - Changes in aquifer storage impact upon the lag time (the time taken for the discharge to reach equilibrium). A smaller specific storage value of 1 x 10^{-6} /m causes a quicker response in discharge related to changes in recharge (shorter time lag). A larger specific storage value of 1 x 10^{-4} /m results in increasing time lag from several thousand years to several tens of thousands of years for the same reaction.
- J aquifer Kh - A tripling of J aquifer Kh results in a shorter timelag between stabilisation of recharge and discharge from several thousand years to just a few hundred years, and total flow through the model in the current condition could be doubled. Conversely, when J aquifer Kh is reduced to one tenth, time lag increases from several thousand years to several tens of thousands of years, and total flow through the system reduces to just over a third.
- Permian aquifers Kh - The model is less sensitive to changes in hydraulic conductivity of the Permian aquifers, with less impact on both lag time and total flow through the system. Increasing (higher value) or decreasing (lower value) Kh result in an estimated time lag between recharge and discharge of several thousand years. Flow volume through the system is within +/- 20% of base case.
- Diffuse recharge - Sensitivity to diffuse recharge is significant in steady state model. Increasing diffuse recharge from 5 mm/y to 15 mm/y results in an increased total flow volume by more than 50%. But this change has only minor effect on time lag (reduces from 7000 to 5000 years).

Table 5-2 Summary table of sensitivity testing results

Sensitivity test	Maximum head along NW margin (m AHD)		Total inflow (ML/d)		Sources of inflow – current condition (%)			Total outflow (lateral) (ML/d)		Time lag between recharge and discharge (years)
	Steady state	Current condition	Steady state	Current condition	River rch	Diffuse rch	Lateral inflow	Steady state	Current condition	
Base case	210	185	156	116	33%	1%	66%	156	119	7000
J aquifer Kh = 0.7 m/d	345	265	104	44	82%	3%	15%	104	47	30000
J aquifer Kh = 21 m/d	180	165	289	245	16%	1%	84%	290	250	500
Purni Fm Kh = 0.1 m/d, Crown Pt Fm = 0.1 m/d	250	190	149	108	36%	1%	63%	149	110	7000
Purni Fm Kh = 2.5 m/d, Crown Pt Fm = 5.0 m/d	190	175	178	139	28%	1%	71%	178	141	4000
Specific storage = 1 x 10^{-6} / m	210	185	156	116	33%	1%	66%	156	119	~0
Specific storage = 1 x 10^{-4} / m	210	190	156	109	35%	1%	63%	156	132	55000
Diffuse rch = 15 mm/y	285	185	247	116	33%	1%	66%	248	118	5000

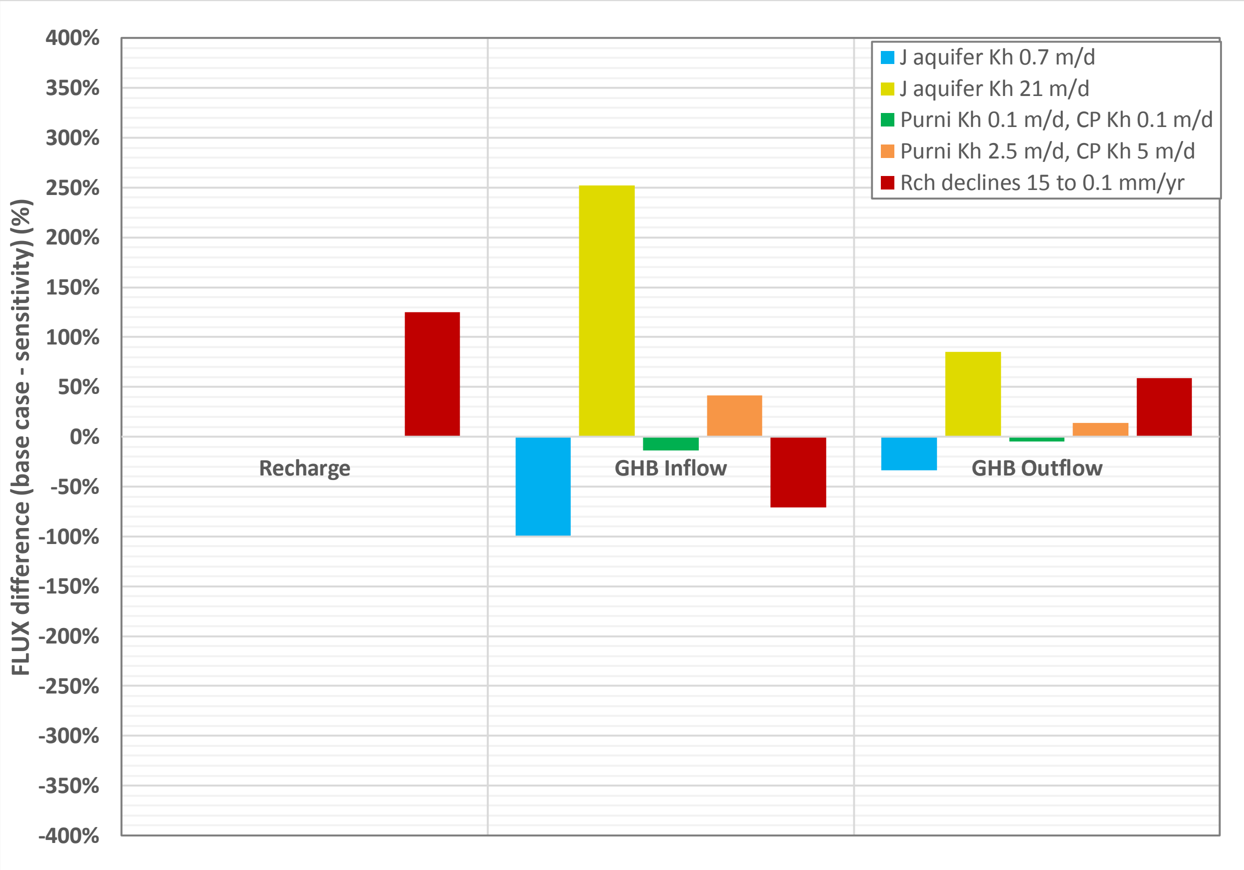

Figure 5.4 Sensitivity of steady state model water balance (variation from base case as %)

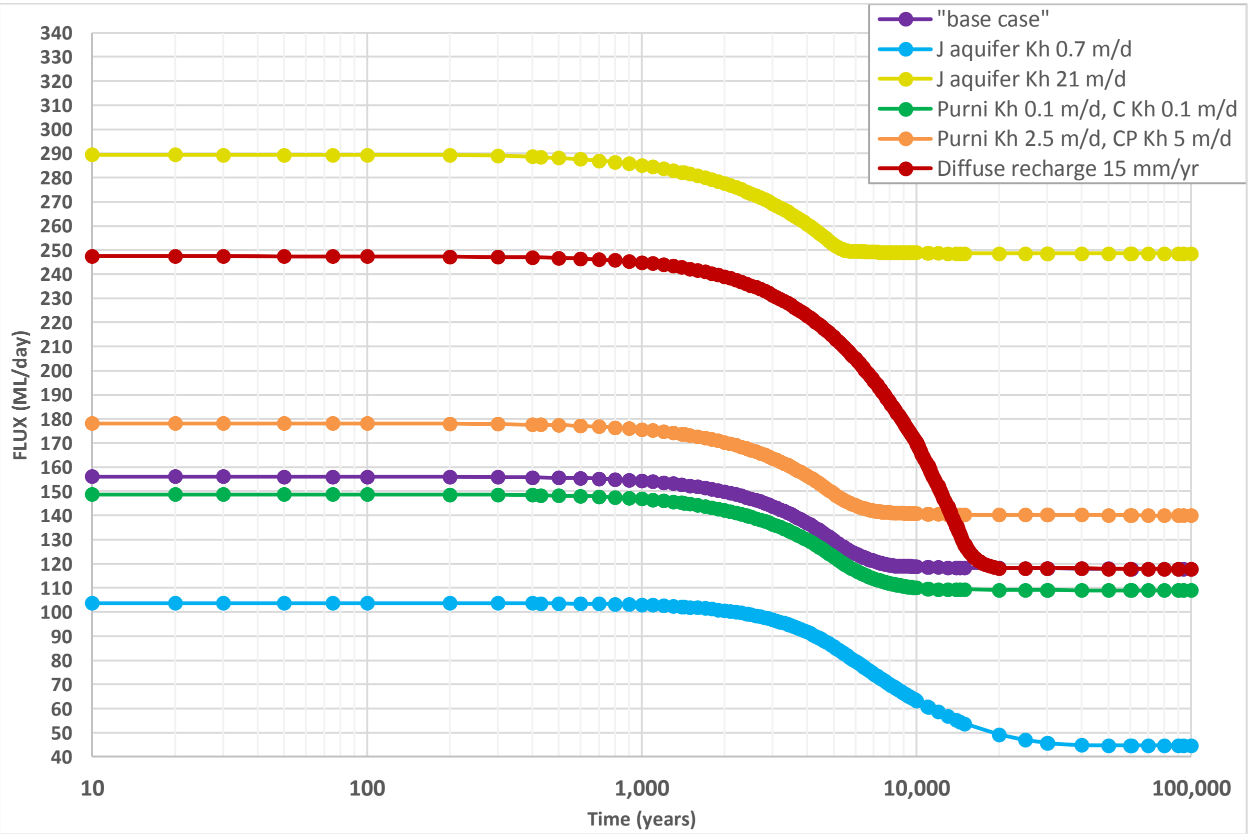

Figure 5.5 Sensitivity of regional discharge

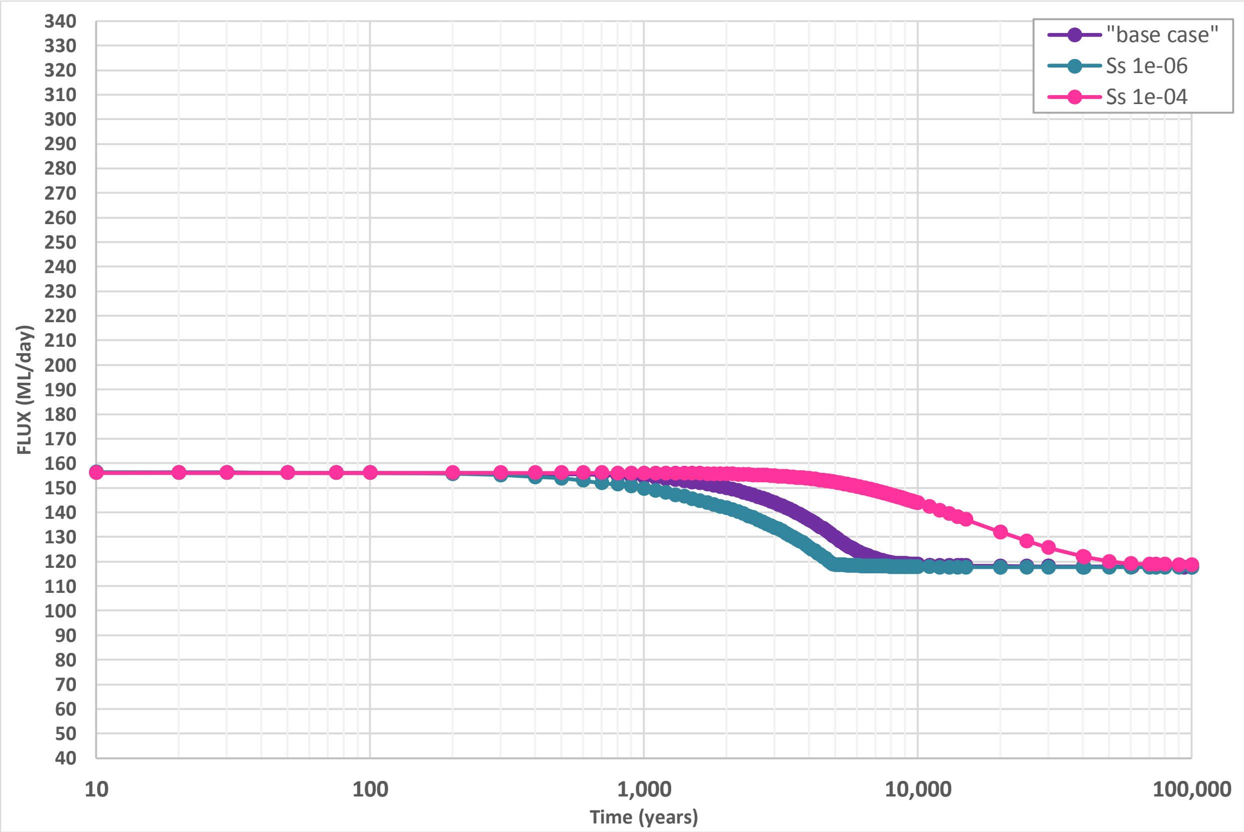

Figure 5.6 Sensitivity of lag time (specific storage)

5.2 Sensitivity to stresses – Mine dewatering test

5.2.1 Description

The objective of this stress test is to sense the potential impact of dewatering at a hypothetical mine location on the regional groundwater systems. The test is purely hypothetical and the result is considered to be of low confidence, given that the model is not calibrated for that purpose and there is limited data to constrain the regional model.

The hypothetical location is situated in the vicinity of where Stage 2 drilling investigations have encountered coal beds at approximately 40 m below the top of the Purni Formation (Figure 5.7). MODFLOW Drain Package is used to simulate the effects of mine dewatering. As the model simulates dewatering using drain cells, the model test does not consider the construction time taken to dewater the aquifer to the top of the coal.

The drain cells are simulated over an area of 1 km^2. The transient-model water levels at the end of the model simulation period were used as initial conditions, and are assumed to reflect a system in equilibrium and the estimations are not mixed with system changes due to other factors. The bed of the drain cells is situated at an elevation of -313 m AHD, which corresponds to a depth of approximately 475 m bgl (approximately 40 m below the top of model Layer 4). The conductance applied to the drain cells is 125 000 m^2/d which minimises resistance so that target drawdown can be achieved.

The dewatering activity is simulated over a period of 50 years, with yearly stress periods. The model was run for 50 years and does not evaluate the recovery in the system after mining has ceased.

5.2.2 Results

The test result indicates that approximately 7190 GL discharged from the drain cells over a period of 50 years (an average of 394 ML/d) to achieve maintaining the target level (Figure 5.8).

The estimated drawdown at 50 years is widespread across the basin (Figure 5.9 and Figure 5.10) and occurs at considerable distance from the mine site. Drawdown contours in the Permian aquifer at distance from the mine site are influenced by the presence of the Triassic sediments.

The modelled water level hydrograph at 3 O'Clock Creek Bore area was show in Figure 5.11. The area is approximately 125 km from the mine site (Figure 5.9) and is located at the edge of the basin closest to the Dalhousie Springs. The model estimates a 7 year time lag from commencement of dewatering to impact shown at the bore. Modelled drawdown is 3 m and is still declining at 50 years. The J aquifer is the main aquifer associated with the GAB springs in the area and it remains artesian over the 50 years (Figure 5.11).

The model assumes the J aquifer and Permian aquifers are well connected, both horizontally and vertically. Geological structures (e.g. faults) that may act as barriers have not been considered. The regional transmissivity of the aquifers could be overestimated, which will impact influence area and the degree of drawdown at a distance from the site.

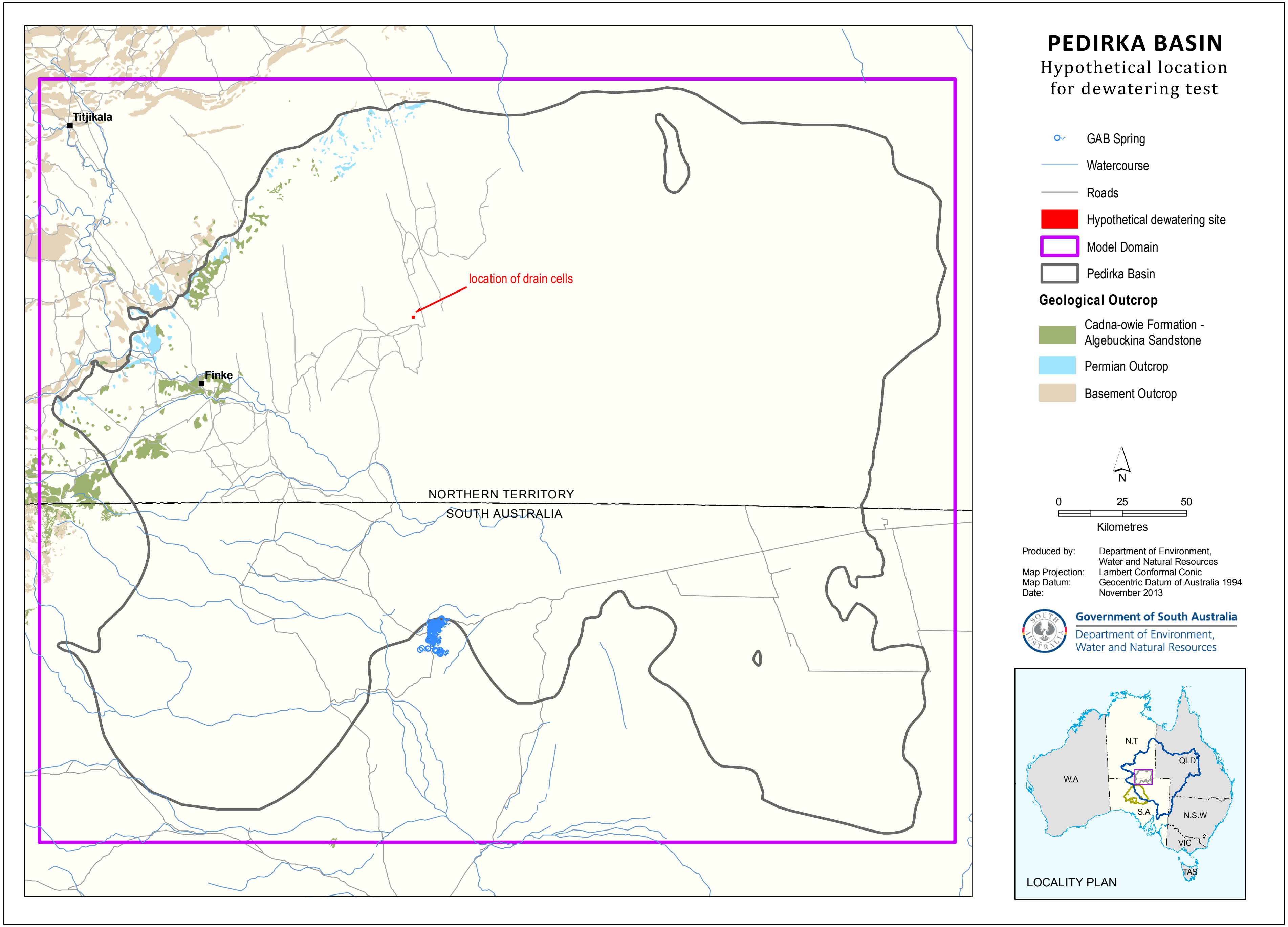

Figure 5.7: Hypothetical location for dewatering test

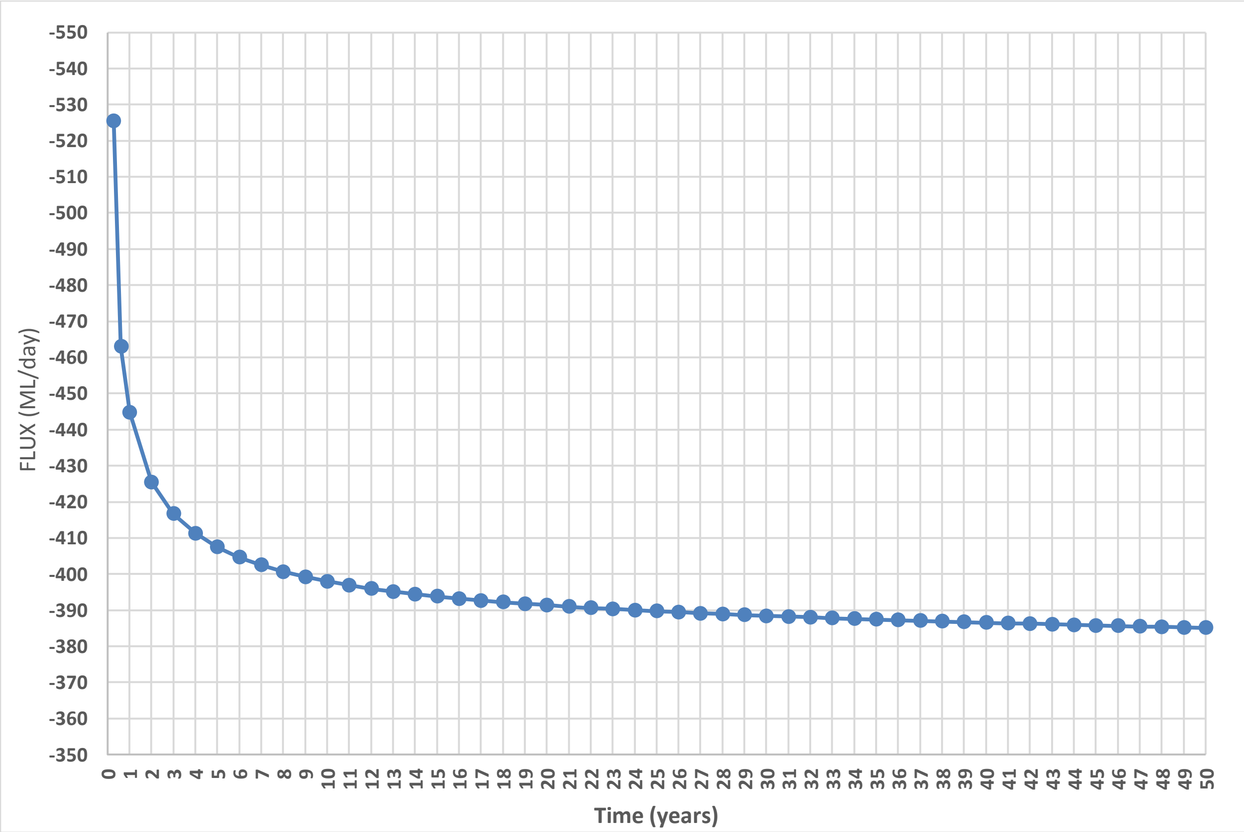

Figure 5.8 Estimated flux to drain cells over 50 year period

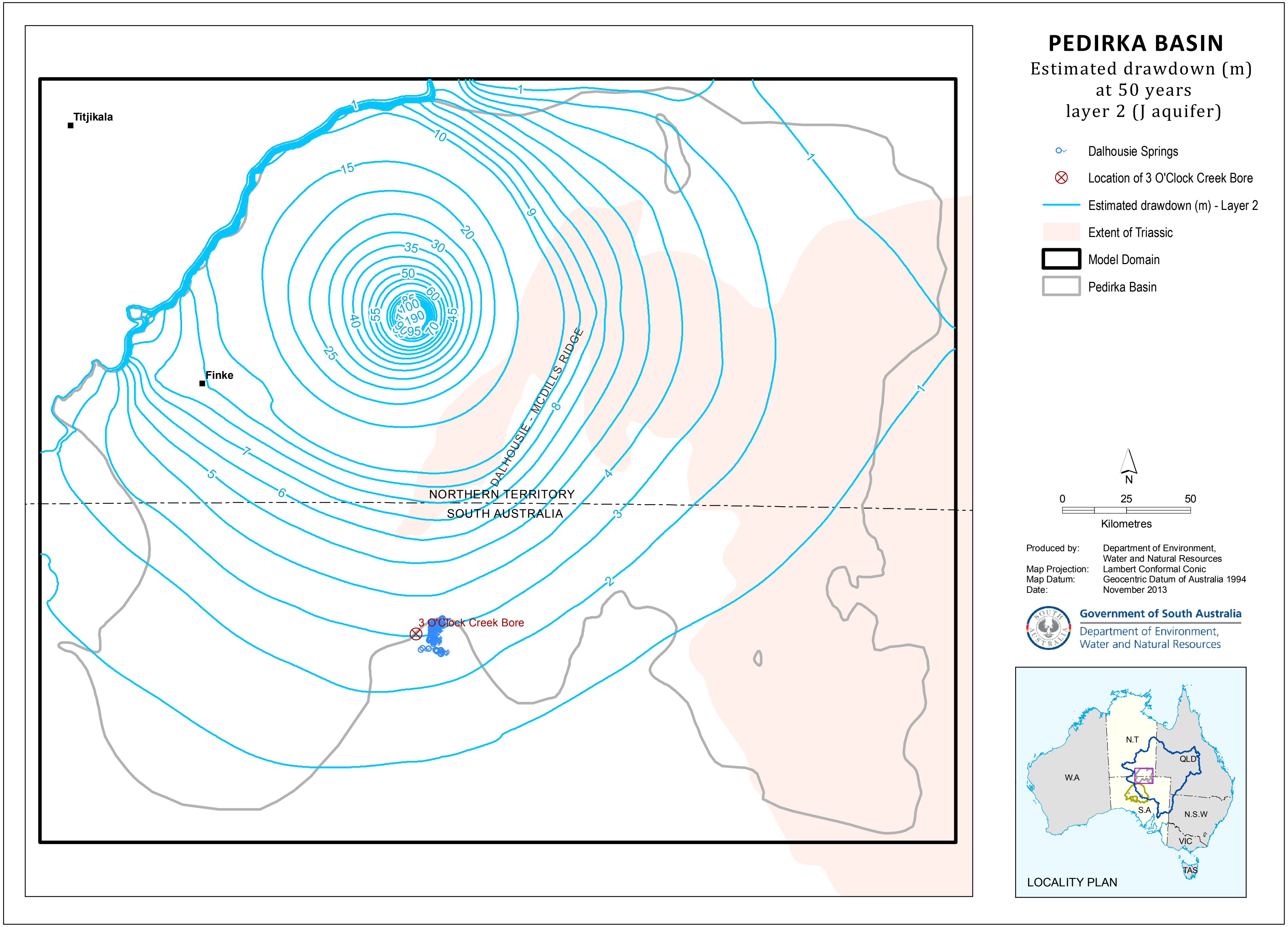

Figure 5.9: Estimated drawdown in layer 2 (J aquifer) at 50 years

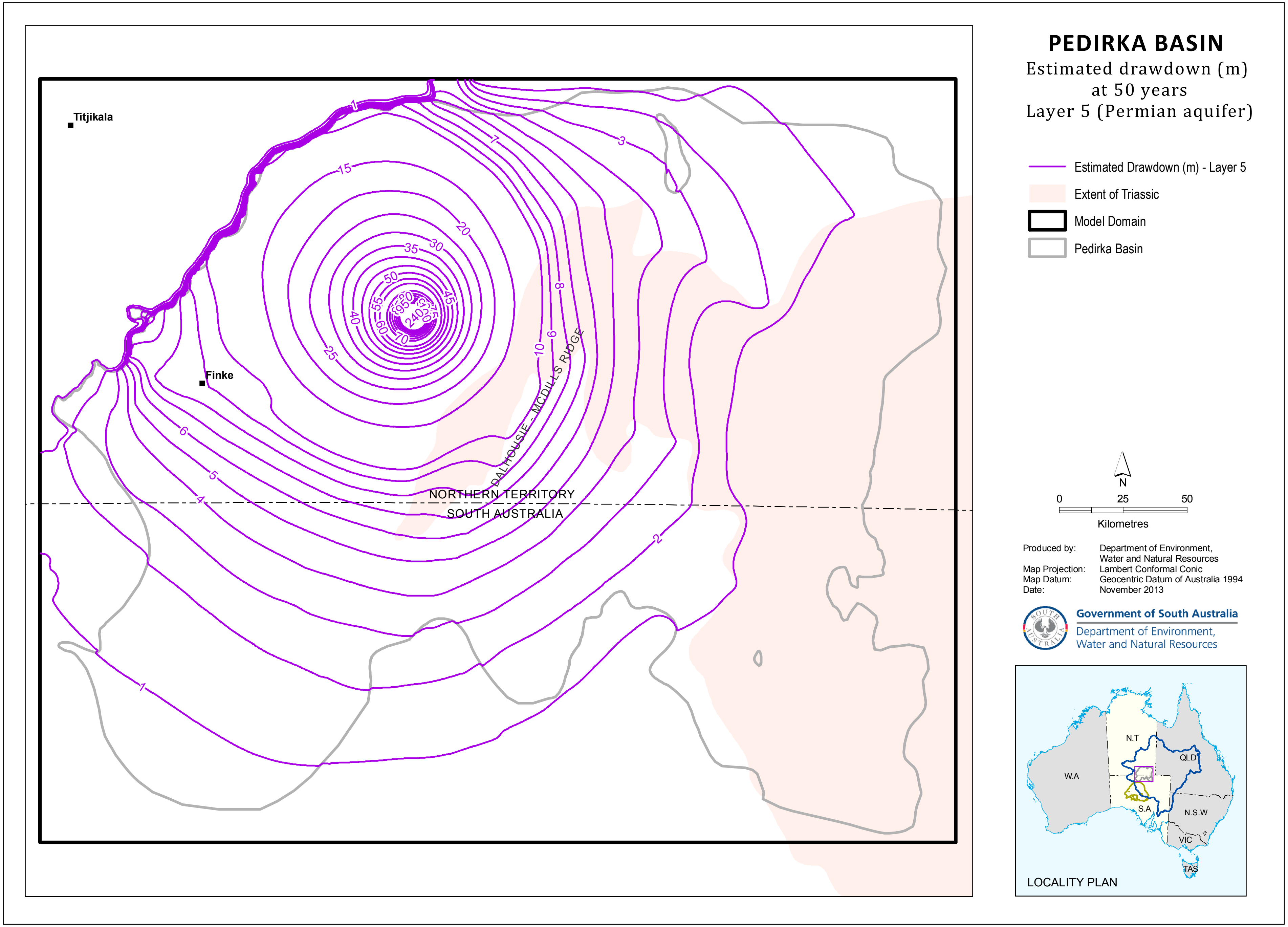

Figure 5.10: Estimated drawdown in layer 5 (Permian aquifer) at 50 years

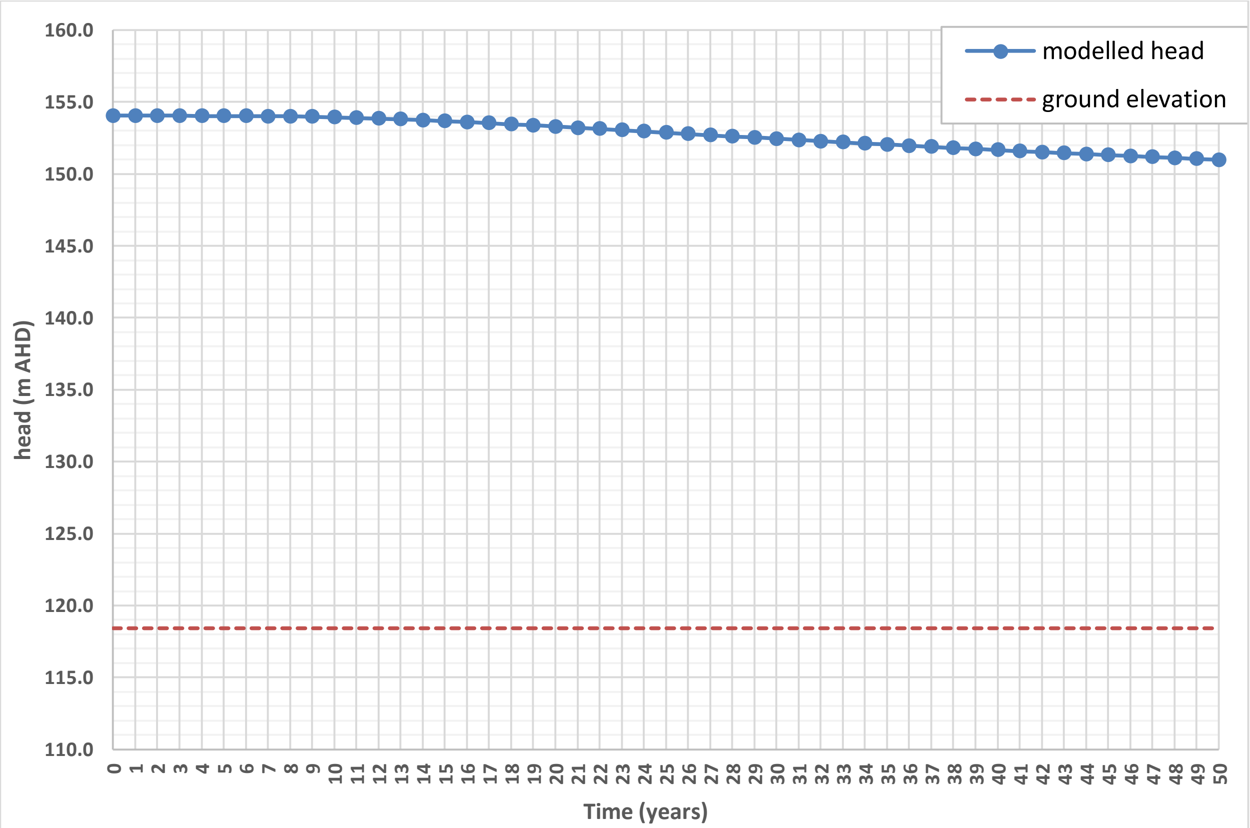

Figure 5.11 Estimated water level (m AHD) in Three O'Clock Creek bore – J aquifer

5.3 Uncertainty analysis

5.3.1 Description

The traditional approach to uncertainty analysis is to select input parameters that are poorly known and/or highly heterogeneous which have impact on key scenario outputs. The parameters are varied within reasonable bounds, based on available data and current knowledge.

For this project, uncertainty analysis focuses on addressing one model simplification and evaluating the affect that this simplification has on model results. Modelling all layers as confined not only meets the aquifer condition in most basin area, but also improves model stability and reduces computation time (refer to Section 3.5). However it is recognised that this approach may impact upon model results on a small area on north-west margin of model domain. In this test, a single simulation is executed in which Layers 2–5 are modelled as type 3 (unconfined/confined), allowing layers to switch between confined or unconfined depending on the calculated water level in relation to the top elevation of the layer. The results of this simulation are compared to the base case.

5.3.2 Uncertainty analysis results

This uncertainty analysis demonstrates that assigning modelling layers as confined leads to overestimation of transmissivity where the water table is situated in the Permian aquifer. This impacts upon modelled water level along the north-west margin in steady state model (Figure 5.13). If the Permian aquifer is modelled as unconfined along the north-west margin, the maximum water level observed is 250 m AHD, which is approximately 40 m higher than the base case model water level in steady state model.

Modelling all layers as confined/unconfined has minor impact on model water balance overall but may lengthen time lag between recharge and discharge by several thousand years (Figure 5.12). This is presumably a consequence of calculation of aquifer transmissivity and storage in the small area along the north-west margin of the model domain.

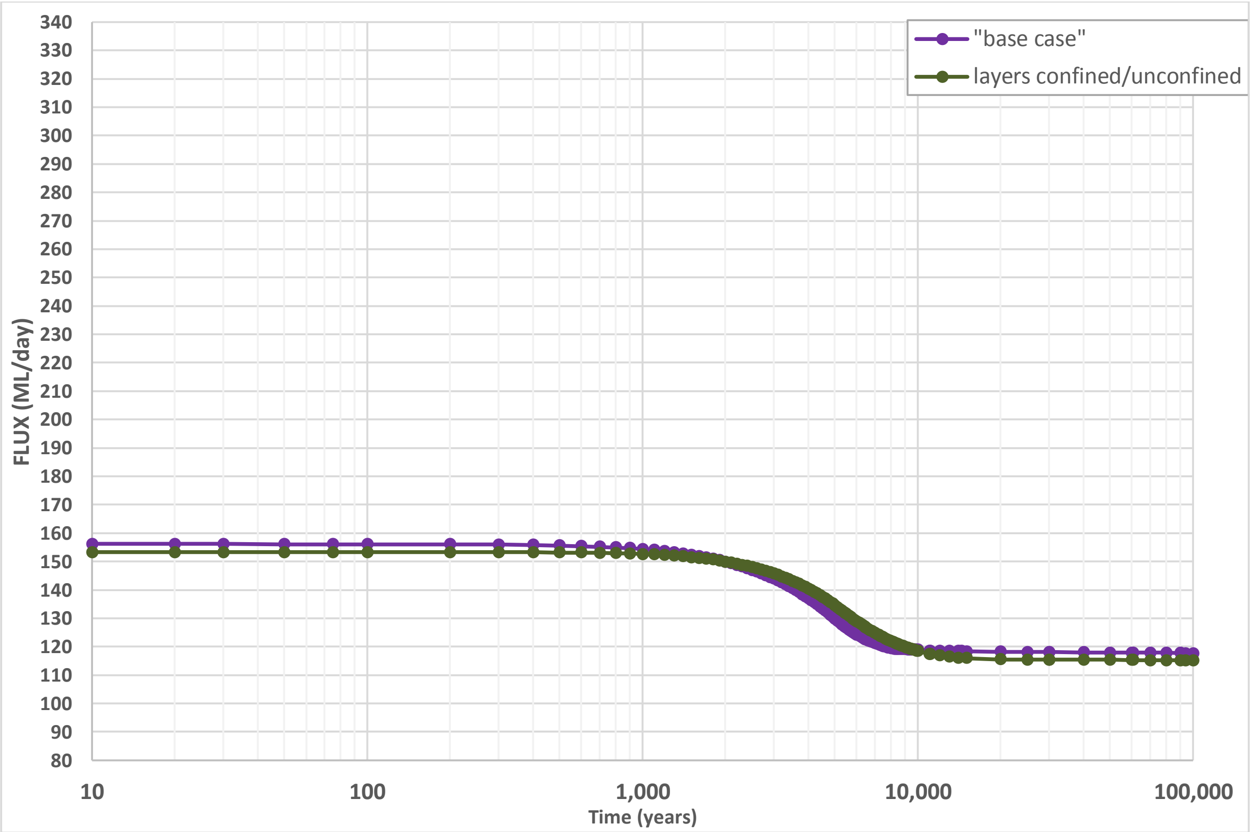

Figure 5.12 Uncertainty test – comparison of discharge

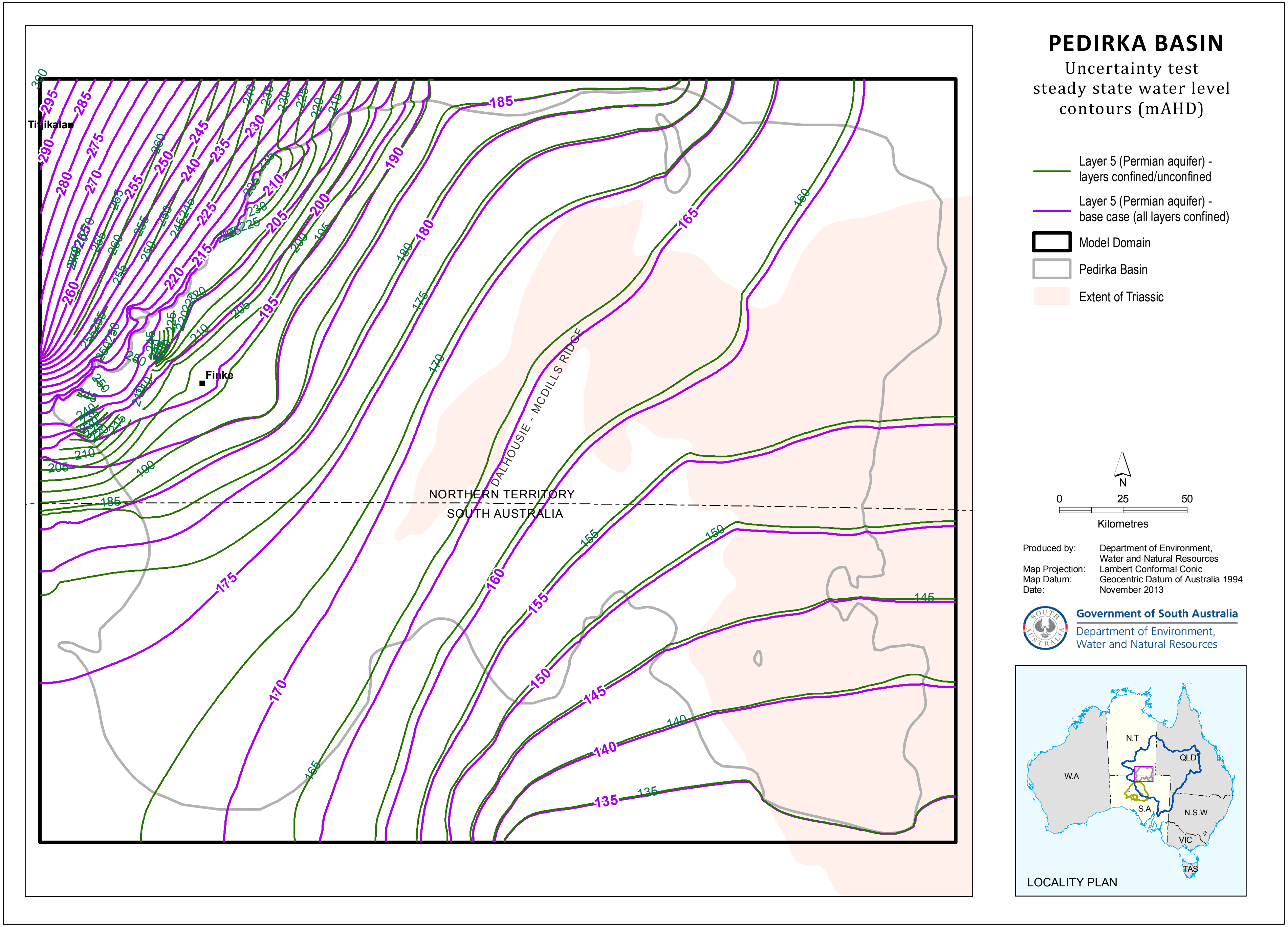

Figure 5.13: Uncertainty test - steady state water level contours (m AHD)

6 Model limitations and capabilities

The MDBC Groundwater Modelling Guideline (2001) states that: It is important to recognise that there is no such thing as a perfect model and all models should be regarded as works in progress of continuous improvement as hydrogeological understanding and data availability improve. By definition, model limitations comprise relatively negative statements and they should not necessarily be viewed as serious flaws that affect the fitness for purpose of the model, but rather as a guide to where improvements should be made during work.

The NWC Australian Groundwater Modelling Guidelines (2012) state that: the capabilities and limitations section is intended to explicitly describe the capabilities and limitations of the model. This section states what the model should and should not be used for, so that expectations of the model can be managed. Limitations of data and code, the reliability of different outcomes of the model and how further data collection or research may improve reliability should be described.

6.1 Model limitation

The model limitations and capabilities are reflecting a number of factors which include the purpose of the modelling project, data availability, time and budget, and limitations in the available science. Computational and model package limitation may also constrain model simulation accuracies. The capability and limitations discussed in this section are mainly associated with the simplifications, limitation of the data, assumption about conditions in the past and choice of numerical code.

Model simplifications, which considered impact to the model results for the purpose of the project, are listed below:

1. The MODFLOW package does not simulate density effects due to temperature gradients which may drive the system in the basin.
2. No detailed aquifer/aquitard parameter distributions were applied in any hydrogeological unit due to data limitations. Regionally representative aquifer parameters were estimated from available data and were tested during sensitivity analysis.
3. Geological structure such as faults were not simulated as physical model barriers.
4. The Triassic was postulated to limit the hydraulic connectivity between the Permian aquifer and the J aquifer, however there was no quantitative data available to estimate hydraulic parameters.
5. No quantitative data exists to inform the storage of the Permian aquifer in the region.
6. The model layer elevations were necessarily approximate and do not reflect the full heterogeneity of the system (this limitation is true of all models).
7. It was assumed that the there was no modelled discharge from the J aquifer to shallower Cainozoic aquifers through the Rolling Downs Group. This was assumed to have limited impact upon the model results for this project.
8. All layers were modelled as confined, which may consequently overestimate aquifer transmissivity and underestimate storativity at a small area along the north-west margin of the basin. It was confirmed that this had minor impact upon the model result for the project.
9. A hypothetical trend in palaeo-diffuse recharge was considered, where recharge linearly declines at a rate of 1 mm/y every 1000 years in response to dryer climate.
10. Diffuse recharge only occurs along the north-west margin of the basin and was not spatially distributed.
11. Recharge from Finke River and Goyder Creek was assumed constant over the model simulation period of 100 000 years.

12. The model does not simulate groundwater pumping from either the J aquifer or Permian aquifers due to lack of available and reliable data.
13. The model does not simulate groundwater discharge from Dalhousie Springs.
14. The model cannot be used to estimate impacts quantatively on a local scale.

Simplifications to the model were made to meet the project requirements and improve model stability and reduce computation time.

6.2 Model capabilities

The development of a groundwater model for the Pedirka Basin was influenced by factors such as purpose of the project, budget, and existing data and information. The model was not calibrated due to limited data and information which is required to adequately constrain the model.

It should be recognised that the model results has limitations for use for other purposes. The accuracy and completeness of data, as well as all assumptions and simplifications should be notified when interpreting the model result.

The groundwater model developed for the Pedirka Basin is considered an adequate starting point from which the model can be improved and upgraded when more data is available. The model could be upgraded further to conduct more sensitivity tests on regional scale impacts. It should be noted that without further refinements, the existing regional scale model cannot be used to evaluate the detailed impacts of local scale activities.

7 Conclusions and recommendations

A regional scale, elementary MODFLOW groundwater model has been developed for the Pedirka Basin using available data, current knowledge and information. Model confirmation process was conducted to ensure the model simulates the system and provides similar water level and flow directions as measured. This model was used to conduct sensitivity tests and uncertainty tests. The outcomes from the modelling process are:

1. Regional Scale Water Balance was obtained from the steady state model which represents a condition in the past and the transient model period that is similar to the current condition. The model simulation shows that potentially the rate of diffuse (rainfall) recharge may have reduced from (~5 mm/y) in past to current rate of (~0.1 mm/y). This change could result in approximately 30% reduction of total recharge to the basin. Model results also show that discharge from the basin may not reach equilibrium with recharge for several thousand years and water level declines around 30 mm/100 years which meet the current knowledge and conceptual model.

2. Sensitivity tests were undertaken to assess changes in aquifer conductivity, specific storage and diffuse recharge. The tests gained better understanding of which component drives the system in the basin. The results show that changes to the storage value has much less impact on the system. The hydraulic conductivity (Kh) of the J aquifer is most sensitive, but larger or smaller Kh for the J aquifer could lead the model further away from measured data and the “base case” model. Increasing diffuse recharge could result in water level changes in the recharge area and change lag time to the discharge.

3. The stress test was conducted to test potential regional scale impact of a hypothetical mine dewatering. The model result indicates that the drawdown in the J aquifer may be a few metres at the south edge of the basin (around Dalhousie Springs) at 50 years. The test indicates that the lag time between dewatering and impact on edge of the basin could be several years.

4. Uncertainty analysis was conducted to evaluate potential numerical errors due to simplified representation of all aquifers as confined, and associated impact on model results. The test result demonstrates that the approach may lead to overestimation of aquifer transmissivity in a small area along the north-west margin. The impact on water level in the small area could be approximately 40 m higher and there is minor change to regional water balance (2%). The estimated time lag is a little long for regional discharge to reach equilibrium after recharge has stabilised.

5. Data, information and knowledge gaps were identified during the modelling process. Table 7-1 below lists the data requirements prioritised based on modelling needs. This can be considered for planning future field and research work.

Table 7-1 Data gaps

Data gaps	Predicted significance
Potentiometric surface and groundwater flow direction	High
Hydraulic parameters of aquifers and aquitards	High
Diffuse recharge (palaeo-recharge estimated through climate modelling)	High
Diffuse discharge (via J aquifer to shallower aquifers; particularly along Dalhousie-McDills Ridge – e.g. sources of discharge to Dalhousie Springs)	High
Ephemeral river recharge	Medium
Improved representation of geological layer surfaces	Medium
Significance of geological structures on groundwater flow	Medium
Interaction between basement and overlying aquifers	Medium
Groundwater extraction	Low

A comprehensive data and information package was developed. It includes data, model files, report and documents associated with the modelling exercise. The filing structure and naming convention was adopted from the DEWNR Groundwater Model Warehouse.

RECOMMENDATIONS

Under the given data constraints, the current model is considered a low confidence, Class 1 model (Barnett et al., 2012). It is fit for purpose of the current project but needs to be upgraded as more data and better information is gained. The following is an outline of recommendations for modelling purposes only:

1. The model can be upgraded and calibrated as new data becomes available. Current field investigations (drilling and aquifer testing, Pedirka Basin aquifer connectivity investigation) will enable better understanding of the hydrogeology. It is recommended that this data and knowledge be used to refine the conceptual model and upgrade the numerical model.
2. During the modelling exercise, significant data gaps were identified. It is recommended that this information be considered for future investigation and research projects. Developing an improved understanding of physical processes, such as the source and volume of water discharging to Dalhousie Springs, will aid in refining the conceptual model and better constraining the numerical model.
3. Currently the model cannot be used to estimate impact and provide high level accuracy results at the local scale. The outcomes from this project can be used to guide local-scale model development for other assessments.
4. Sensitivity tests were undertaken during the current modelling exercise, varying several parameters and boundary conditions. It is recommended that future modelling exercises consider a more comprehensive sensitivity analysis that includes:
   - Assessing the sensitivity of the model to properties of the Triassic
   - Assessing the sensitivity of the model to different Kh/Kv ratios for the aquifers
   - Assessing the sensitivity of the model to boundary conditions, including the general head boundary of Layers 4-6 and conductance assigned to general head cells

5. The model was developed with limited data and the combination of different uncertainties with regard to parameters and boundary conditions presented a challenge for basin-scale modelling. Potentially there may be several different combinations of hydraulic parameters, recharge and boundary conditions which could be used to form a similar model but provide different model results. To gain a best combination, sensitivity tests need to be conducted which potentially need to run hundreds of different combinations of realisations. This test requires sufficient time, budget and computer capability. This detailed sensitivity and uncertainty analysis is recommended for future works.

Units of measurement

Units of measurement commonly used (SI and non-SI Australian legal)

Name of unit	Symbol	Definition in terms of other metric units	Quantity
day	d	24 h	time interval
gigalitre	GL	10^6 m^3	volume
gram	g	10^{-3} kg	mass
hectare	ha	10^4 m^2	area
hour	h	60 min	time interval
kilogram	kg	base unit	mass
kilolitre	kL	1 m^3	volume
kilometre	km	10^3 m	length
litre	L	10^{-3} m^3	volume
megalitre	ML	10^3 m^3	volume
metre	m	base unit	length
microgram	µg	10^{-6} g	mass
microlitre	µL	10^{-9} m^3	volume
milligram	mg	10^{-3} g	mass
millilitre	mL	10^{-6} m^3	volume
millimetre	mm	10^{-3} m	length
minute	min	60 s	time interval
second	s	base unit	time interval
tonne	t	1000 kg	mass
year	y	365 or 366 days	time interval

Shortened forms

~ approximately equal to

bgs below ground surface

K hydraulic conductivity (m/d)

Ss Specific storage (1/m)

Glossary

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

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

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

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

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

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

Bore — See 'well'

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

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

Confining layer — A rock unit impervious to water, which forms the upper bound of a confined aquifer; a body of impermeable material adjacent to an aquifer; see also 'aquifer, confined'

DEWNR — Department of Environment, Water and Natural Resources (Government of South Australia)

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

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

Fully-penetrating well — In theory this is a wellhole that is screened throughout the full thickness of the target aquifer; in practice, any screen that is open to at least the mid 80% of a confined aquifer is regarded as fully-penetrating

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

GIS — Geographic Information System; computer software linking geographic data (for example land parcels) to textual data (soil type, land value, ownership). It allows for a range of features, from simple map production to complex data analysis

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

Hydraulic conductivity (K) — A measure of the ease of flow through aquifer material: high K indicates low resistance, or high flow conditions; measured in metres per day

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

Hydrography — The discipline related to the measurement and recording of parameters associated with the hydrological cycle, both historic and real time

Hydrology — The study of the characteristics, occurrence, movement and utilisation of water on and below the Earth's surface and within its atmosphere; see also 'hydrogeology'

Impact — A change in the chemical, physical, or biological quality or condition of a water body caused by external sources

Infrastructure — Artificial lakes; dams or reservoirs; embankments, walls, channels or other works; buildings or structures; or pipes, machinery or other equipment

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

Lake — A natural lake, pond, lagoon, wetland or spring (whether modified or not) that includes part of a lake and a body of water declared by regulation to be a lake. A reference to a lake is a reference to either the bed, banks and shores of the lake or the water for the time being held by the bed, banks and shores of the lake, or both, depending on the context.

m AHD — Defines elevation in metres (m) according to the Australian Height Datum (AHD)

Model — A conceptual or mathematical means of understanding elements of the real world that allows for predictions of outcomes given certain conditions. Examples include estimating storm run-off, assessing the impacts of dams or predicting ecological response to environmental change

Monitoring — (1) The repeated measurement of parameters to assess the current status and changes over time of the parameters measured (2) Periodic or continuous surveillance or testing to determine the level of compliance with statutory requirements and/or pollutant levels in various media or in humans, animals and other living things

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

Natural resources — Soil, water resources, geological features and landscapes, native vegetation, native animals and other native organisms, ecosystems

Observation well — A narrow well or piezometer whose sole function is to permit water level measurements

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

Piezometer — A narrow tube, pipe or well; used for measuring moisture in soil, water levels in an aquifer, or pressure head in a tank, pipeline, etc

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

Production well — The pumped well in an aquifer test, as opposed to observation wells; a wide-hole well, fully developed and screened for water supply, drilled on the basis of previous exploration wells

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

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

Specific storage (S_s) — Specific storativity; the amount of stored water realised from a unit volume of aquifer per unit decline in head; it is dimensionless

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

(S) — Storativity; storage coefficient; the volume of groundwater released or taken into storage per unit plan area of aquifer per unit change of head; it is dimensionless

Surface water — (a) water flowing over land (except in a watercourse), (i) after having fallen as rain or hail or having precipitated in any another manner, (ii) or after rising to the surface naturally from underground; (b) water of the kind referred to in paragraph (a) that has been collected in a dam or reservoir

T — Transmissivity; a parameter indicating the ease of groundwater flow through a metre width of aquifer section (taken perpendicular to the direction of flow), measured in m^2/d

TDS — Total dissolved solids, measured in milligrams per litre (mg/L); a measure of water salinity

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

Transmissivity (T) — A parameter indicating the ease of groundwater flow through a metre width of aquifer section

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

Water body — Includes watercourses, riparian zones, floodplains, wetlands, estuaries, lakes and groundwater aquifers

Watercourse — A river, creek or other natural watercourse (whether modified or not) and includes: a dam or reservoir that collects water flowing in a watercourse; a lake through which water flows; a channel (but not a channel declared by regulation to be excluded from the this definition) into which the water of a watercourse has been diverted; and part of a watercourse

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

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