Department of Water
Government of Western Australia

Perth Regional Aquifer Modelling System (PRAMS) model development: Hydrogeology and groundwater modelling

Hydrogeological record series

Looking after all our water needs

Report no. HG 20
September 2008

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Cover photo: Perth city skyline, March 2005 (photo Glyn Kernick)

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Summary

The Perth Region Aquifer Modelling System (PRAMS) has been developed by the Department of Water and Water Corporation, in conjunction with CyMod Systems and CSIRO, for the development of sustainable water management strategies. This model system is an interactive and predictive tool for quantitative water resource assessment, evaluating impacts of land and water use options on the environment, and determining sustainable water resource management options.

This volume of the PRAMS report series describes geology and hydrogeology, with over 100 maps generated with GIS based on Davidson (1995) and new data. The report can be used as both a stand alone geology and hydrogeology report, and a document for the PRAMS model development.

The study area is within the Swan Coastal Plain and Dandaragan Plateau to a distance of about 150 km north of Perth and 70 km south of Perth. It covers an area of 9100 km^2, including over 2000 km^2 offshore area – about twice the area covered by GSWA Bulletin 142. The study produced new geological and hydrogeological maps for the Northern Perth Region (Gingin) and the offshore area. It provided estimated hydraulic properties for 23 geological units that were grouped into the superficial, Mirrabooka, Leederville and Yarragadee aquifers, and several regional confining beds. The study also established a new aquifer, namely the Parmelia Sand aquifer – a local confined aquifer beneath the Dandaragan Plateau.

The study consisted of a detailed account of groundwater use and its historical trends. It also estimated the amount of rainfall recharge to the superficial aquifer. The study also found that the relationship between drains and groundwater was seasonally dependent, based on streamflow and baseflow analyses.

The study established a 12-layer conceptual hydrogeological model that represents seven aquifers and five confining beds to a depth of 3000 m, and described major hydrological processes. A numerical model PRAMS has been developed based on the conceptual model and described in other volumes of the PRAMS report series.

1 Introduction

1.1 Location

The location and area of the Perth Region Aquifer Modelling System (PRAMS) is shown in Figure 1. The area is referred to as the Perth Region, and covers an area of about 9100 km^2 (7100 km^2 onshore and 2000 km^2 offshore). It is bounded to the north by the northern boundary of the Gingin Groundwater Area (from Grey at the coast to Dandaragan and Moora to the east), to the south by the Murray River system, to the east by the Darling Fault, and to the west by a composite line drawn along the Warradarge Fault, Lesueur Fault and offshore faults. The region lies within the Perth Basin and occupies that part of the Swan Coastal Plain and Dandaragan Plateau to a distance of about 150 km north of Perth and the Swan Coastal Plain to about 70 km south of Perth. The study area is divided into Perth north, Perth central and Perth south areas. Perth north is located between the northern model boundary and the Gingin Brook and comprises the Gingin Groundwater Area. Perth central is located between the Gingin Brook and the Swan River and comprises the Gnangara Groundwater Mound and northern Perth urban area. Perth south is located between the Swan River and Mandurah and includes the Jandakot Groundwater Mound.

The main difference between this study and Geological Survey of Western Australia (GSWA) Bulletin 142 (Davidson, 1995) is that this study covers about twice the area considered in Bulletin 142. The newly mapped areas include Perth north, or Gingin Groundwater Area, and about 2000 km^2 offshore area.

1.2 The Perth Region aquifer modelling project

Groundwater provides up to 50 per cent of the scheme water requirement and up to 80 per cent of the total water requirement of the Perth Region. It is used for scheme water supplied by the Water Corporation, licensed private supply, and household gardens. Groundwater is also utilised by forests managed by the Department of Environment and Conservation (formerly Department of Conservation and Land Management (CALM)) and other groundwater-dependent ecosystems.

The groundwater resources are contained in a multi-layered aquifer system in sediments of the Perth Basin that range in age from Jurassic to Quaternary. Owing to lower than average rainfall over recent years, together with increasing groundwater utilisation, groundwater levels have been declining. For these and other management reasons, a common computer groundwater modelling system is required by the Department of Water (formerly Water and Rivers Commission (WRC)) and Water Corporation. PRAMS has been developed to evaluate the groundwater resource and its availability and sustainability for production. This model is an interactive and predictive tool for quantitative water resource assessment, evaluating effects of different management and development scenarios, assessing impacts of land and water uses on wetlands, and determining optimal management practice.

1.3 Purpose and scope

The purpose of this project was to develop a groundwater modelling system that enables the Department to manage the water resources sustainably. This has been achieved through cooperation between the Department of Water and Water Corporation as participating partners of the project.

The modelling project consists of a feasibility study, model development, and preparation of supporting documents. This volume of the PRAMS report series describes geology, hydrogeology and the conceptual model of the Perth Region Aquifer Modelling System. Yu et al. (2002) presented early results of the model development. Data from previous studies, including Allen (1976, 1981a, 1996, 1997), Briese (1979), Commander (1974), Kern (1993), Moncrieff (1989), Moncrieff and Tuckson (1989), and especially Davidson (1995), together with the collection of new data, have been used to generate new maps using a Geographic Information System (GIS) and database.

Groundwater modelling has been proven to be an interactive and predictive tool for quantitative groundwater resource assessment, evaluating environmental impacts of land and water use options, and providing scientific data for the development of sustainable water allocation and environment protection plans.

The aim of both the Department of Water and Water Corporation is to utilise the groundwater resources in a sustainable manner for the benefit of the community and State. For this to proceed efficiently, a modelling system common to both agencies is required. Water Corporation had the responsibility for developing the unsaturated aspect of the model (the vertical flux model). The Department of Water has been responsible for developing the saturated aspect of the model down to the base of the Yarragadee aquifer, a maximum depth of about 3000 m.

In an agreement signed by both the Department of Water and Water Corporation, it is stated that both organisations will provide all necessary and available data for the satisfactory development of the modelling system and that ownership of these data will be shared by both organisations. It was also agreed that the Department, as manager of water resources and custodian of water information, will be responsible for the management and maintenance of the GIS database. Funds for this activity will be derived, in part, from fees obtained from all third party users of the system. Any proceeds obtained by the Department or the Corporation will be divided according to the ratio of agreed investment in the project.

The Department will utilise the model as a management tool to quantify the groundwater resources, determine the environmental water requirements, assess the effect of private and public groundwater abstraction on wetlands, and provide information for fair and equitable trading and licensing of groundwater allocations. The Corporation will use the model to help develop groundwater supply schemes, run scheme abstraction scenarios, manage groundwater levels for environmental purposes, and as a predictive tool.

1.4 Previous work

1.4.1 Hydrogeological investigations

The history of hydrogeological investigations within the Perth Region has been summarised by Allen (1976, 1979, 1981a, 1996, 1997) and Davidson (1995). Major and systematic exploratory drilling was commenced in 1961 and continued through to about 1990. In Perth central (between Gingin Brook and Swan River), Morgan (1964), Whincup (1966), Sanders (1967), Allen (1977, 1980) and Davidson (1977) described the results of drilling exploratory bores. It was found that large quantities of groundwater are available but that the salinity of the groundwater generally increased both towards the west and with increasing depth. In Perth north (between Moora and Gingin Brook), Briese (1979), Moncrieff (1989), and Moncrieff and Tuckson (1989) summarised geological information along Gingin Brook, Gillingarra, and Moora exploration lines. Kern (1993) studied the geology and hydrogeology of the superficial formations between Cervantes and Lancelin. It was found that the Yarragadee Formation in a large area is in direct contact with the superficial formations. In Perth south, Berliat (1964), Emmenegger (1964), Morgan (1969), Commander (1974, 1975) and Allen (1978) described the exploration drilling in areas between the Swan River and Mandurah.

Superficial aquifer investigation projects were carried out in Perth central and Perth south by the Water Authority of Western Australia between 1960 and 1990. Many exploration bores were integrated into the Perth Region groundwater monitoring network. Allen (1976, 1981b) and Davidson (1995) summarised the results of the above investigations.

Allen studied the groundwater resources in the confined aquifers beneath the Perth Region that included all drilling data available to 1978. This work was expanded to include a brief description of the groundwater resources of the unconfined aquifers (Allen, 1981b). Commander (1988) studied the geology and hydrogeology of the superficial formations of the Lake Clifton area. Commander et al. (1991) described the groundwater resources of the onshore Perth Basin, of which about 10 per cent is occupied by the Perth Region. Thorpe and Davidson (1991) assessed the hydraulic characteristics of the aquifers based on analysis of naturally occurring isotopes in groundwater. The study delineated areas of aquifer recharge and estimated the rate of groundwater flow within the confined aquifers of the Perth Region.

In conjunction with the deep exploratory drilling, the results of shallow drilling to investigate the unconfined aquifers of the Perth Region have been reported since the early 1960s. Morgan (1964) reported a drilling program for studying shallow groundwater in the Gnangara area. Since then, many published and unpublished reports have been written. From pumping tests, Balleau (1972) determined the hydraulic characteristics of the shallow aquifer in the Gnangara area, and Allen (1976) synthesised the results of drilling both in the northern and southern Perth areas and made estimates of the unconfined groundwater resources within these areas. Davidson (1984) estimated groundwater throughflow based on flownet analysis within the unconfined aquifers and established a recharge/discharge water balance for the southern Perth area and for a local area to the north-east of Perth.

Scientific research on groundwater recharge and resource assessments have been carried out by Bestow (1971), Sharma et al. (1983, 1991), Farrington (1984), Anson (1985), Sharma and Hughes (1985), Sharma (1986a,b), Sharma and Craig (1989), Thorpe (1989) and Farrington and Bartle (1991). These studies used infiltration tests at selected experimental sites, or naturally occurring isotopes and tracers, to estimate the rainfall recharge to the unconfined aquifers of the Perth Region. These estimates of recharge were made for different landuse and climatic conditions and showed that recharge rates mostly ranged from five per cent to 40 per cent of the rainfall, depending on location and landuse.

More recent hydrogeological investigations include drilling of a Yarragadee aquifer bore for groundwater supply to mineral sand development at Gingin by Iluka Resources (URS, 2002a,b). The drilling found that the Carnac Member of the Parmelia Formation is in direct contact with the superficial formations at shallow depth.

Three exploration bores were drilled along the eastern margin of the Gingin Groundwater Area (Diamond, 2000). The drilling intercepted geological units ranging from the Osborne to the Leederville Formations. This provided detailed information and filled data gaps for this mapping.

Drilling of three Yarragadee production bores for Perth drought relief took place between 2000 and 2001. The drilling intercepted extensive sandstone in the Kings Park Formation and identified a large fresh water source in the Kings Park Formation, which had previously been considered to be a confining bed.

Two deep Yarragadee bores were drilled near Champion Lakes for groundwater supply to the Champion Lakes development (Thorpe, 2003). The pumping test at Bore CL1, which is located in the Serpentine Fault zone, indicated that the permeability and yield of the Yarragadee Formation is significantly reduced due to faulting. However, the pump test at Bore CL2, located near AM48, indicated that the Yarragadee Formation has a good yield. The groundwater salinity is around 3000 mg/L.

1.4.2 Review of groundwater flow modelling

Since the 1970s, there have been three major groundwater flow modelling studies for the Swan Coastal Plain. The first modelling period is characterised by the development of simple water balance or numerical models for groundwater resource assessment (Bestow, 1976; Pollett and Wiese, 1977; Pollett, 1981; Allen, 1981a). Allen (1981a) summarised geological and hydrogeological information and produced a water balance model that included the superficial, Leederville, and Yarragadee aquifers for the Perth metropolitan area.

The second modelling period was initiated in 1982 and produced the Perth Urban Water Balance Model, as part of the Perth Urban Water Balance Study (PUWBS). McFarlane (1983, 1984) carried out a detailed study on effects of urbanisation on groundwater in selected urban areas. The study focused on the shallow groundwater and recognised that urbanisation and rapid increase in groundwater abstraction have posed significant stresses on the environment and may cause problems including a decline in regional water levels, drying wetlands, groundwater contamination and saltwater intrusion. The study produced conceptual models that describe hydrological processes affecting water quality and quantity.

The model development was carried out by the then Water Authority of Western Australia (WAWA), in conjunction with the Geological Survey of Western Australia, and the Centre for Water Research at the University of Western Australia, between 1982 and 1987 (Cargeeg et al., 1987). The PUWBS model comprises a recharge model and a groundwater flow model, and has been used to understand hydrological processes in the Perth metropolitan area, and to predict effects of groundwater and land uses on the superficial aquifer.

The third modelling period started in 1994 as confined aquifers became a significant resource for the public and private water supply. The Perth Groundwater Resource model integrates the PUWBS model with the Perth Artesian Aquifer model developed by Rust PPK (1996a,b). The Perth Artesian Aquifer model is a quasi three-dimensional, three-layered finite element model using AQUIFEM–N (Townley, 1993) to simulate three major confined aquifers – the Mirrabooka, Leederville, and Yarragadee aquifers (Martinick McNulty, 1999).

1.5 A new groundwater modelling system

1.5.1 Feasibility studies

The feasibility studies of establishing a new groundwater modelling system for the Perth Region were carried out by CyMod Systems (1999) and Townley (2000a,b). A set of criteria was defined by the Department of Water and Water Corporation to state the essential and desirable functionality of the modelling system. The purpose of the studies was to review the existing groundwater modelling systems, including PUWBS (Perth Urban Water Balance Study) and the Perth Groundwater Resource Model, and to assess future groundwater modelling options with respect to the strategic modelling needs of both organisations. Yu et al. (2000) summarised the findings of the feasibility studies and concluded that the existing models have structural and algorithm deficiencies and cannot handle the complicated hydrogeological processes and land and water management issues of the Perth Region satisfactorily. It was recommended that the Department of Water and Water Corporation establish a new modelling system. The reports concluded that:

- The existing system was developed with different objectives and limited by aged modelling techniques. It scored the lowest based on the selection criteria set up by the consultants and the Department of Water and Water Corporation modelling team, indicating that the existing systems can no longer meet the modelling requirement. The resources required to bring the existing systems to a level that conforms to the selection criteria would exceed the effort needed to establish a new modelling system. In the context of time and value-for-money, the Department of Water and Water Corporation should not undertake any additional development of the existing systems.

- The Department of Water and Water Corporation should establish a new modelling system. This system will be an improved scientific tool for quantitative groundwater resource assessment, and development of water resource management plans for the Perth Region. It will provide data for assessment of environmental water provision (EWP) and other allocation and protection plans. The new system will provide a user-friendly, secure and quality-assured structure by allowing for effective data sharing through a GIS, database and the Internet among the Department of Water, Water Corporation and other groundwater users.

1.5.2 Selection of modelling software

The feasibility studies also included the selection of modelling software based on the following selection criteria that were set up by the Department of Water and Water Corporation.

The general criteria are that the new modelling system should incorporate the latest modelling techniques such as graphics-based pre- and post-processors, GIS and database linkage, state-of-the-art three-dimensional data visualisation, a regional model coupling 'nested local models' or telescopic mesh refinement capacity, and automated calibration tools. The system should have comprehensive algorithms to deal with groundwater and wetland interactions, the impact of land and water use on water levels, and water exchange between aquifers. The model should use software available in the public domain and meet industrial standards to ensure quality control.

The study recommended that the model development use Modflow-based software to construct a three-dimensional model for simulating groundwater flow in the saturated aquifers, and a separate physical process-based vertical flux model to simulate hydrological processes in the unsaturated zone, and calculate recharge to the watertable. The two parts were to be developed separately and then integrated to form a completed groundwater modelling system.

Groundwater Modelling System (GMS) was developed by the United States Department of Defence and the Engineering Computer Graphics Laboratory at Brigham Young University (EMS-I, 2001). It is a modular and GIS-based modelling system with pre- and post-processors. GMS consists of more than 10 modules that can be used to simulate a broad range of groundwater flow and solute transport processes. Modflow (McDonald and Harbaugh, 1988) is one of the GMS flow modules and has been widely accepted as the industrial standard with proven applications. GMS provides three-dimensional geostatistical and visualisation tools and has direct GIS interface. GMS also provides a functionality that enables a local scale model to be constructed within a regional scale model.

PMWIN (Chiang and Kinzelbach, 2000) was also used for the model development. The software is a simple version of Processing MODFLOW, which is one of the most complete three-dimensional groundwater flow and transport simulation systems. PMWIN provides flexible and simple function for data input/output, and is a very efficient tool for model calibration.

PRAMS Version 2.1 was released in April 2002 (Cymod, 2004). A Vertical flux model (VFM), described bu Silberstein (2004) and Cymod (2004) has been integrated with the saturated model as Version 3.0, released October 2003.The VFM simulates major hydrological processes within the unsaturated zone, in particular the plant root zone. The integration between the vertical flux model and the saturated aquifer model was made by modifying the Modflow codes.

2 Physiography and landuse

2.1 Landuse

Most of the population of the region resides in suburban areas adjacent to the Swan River estuary, along the coast including fishing settlements, and within the south-east corridor to south of Armadale. Small urban areas have also developed to the north and south and most are within rural land cleared for agriculture. The remaining bushland comprises mostly State Forest and Crown Land or reserves and undeveloped private land adjacent to the coast (Fig. 2). Market gardens (horticulture) are located mainly in depressions within the Spearwood Dunes and within low-lying areas between the Spearwood and Bassendean Dune systems where the soil is commonly peaty. Pine forests (silviculture) have been developed over large tracts of sandy soil within the Spearwood and Bassendean Dunes. Vineyards (viticulture) are located on the loamy soils of the Pinjarra Plain, particularly within the Swan Valley. Fruit trees, including olive groves, have been established on the Dandaragan Plateau and form a rapidly growing industry. Elsewhere, cleared agricultural land is used mainly for grazing.

In recent years, significant residential developments have been taking place along the coastal strip and Perth's north-east corridor including Ellen Brook. Extensive urbanisation has also been taking place in Gwelup, Joondalup, Wanneroo, and Lansdale, where market gardens have been subdivided into small residential lots.

Major heavy industrial developments have been established in the Kwinana district. Many smaller industries and commercial areas are located throughout the region, but only the more significant centres are shown on Figure 2.

2.2 Climate

The climate of the Perth Region is Mediterranean in type with hot, dry summers and mild, wet winters. The hot, dry summers are caused by a belt of anticyclones (zones of high pressure) that pass over the region between October and March. Little rainfall is associated with the anticyclones because the air is descending within these high pressure zones. The air that is descending becomes increasingly warm and has a greater capacity to retain moisture.

These weather conditions are usually accompanied by clear skies and high levels of ultraviolet radiation. During the cool winter months, rainfall results from subpolar, low-pressure cells that cross the region as cold fronts. These weather conditions are usually accompanied by strong winds and cloudy skies. In the Perth Region, since about 1968, the high pressure anticyclone belt has moved southward, deflecting the cold fronts to the south of Perth, resulting in a drier climate for the central and southern Perth Region.

The long-term average annual rainfall is 860 mm, based on data collected at the Perth region station at Mount Lawley. It ranges from about 590 mm in the northern coastal area to about 1200 mm on the Darling Plateau, south-east of Perth (Fig. 1). Approximately 90 per cent of the rain falls between April and October and the remaining months are characteristically hot and dry (Fig. 3), resulting in large evaporation losses from wetlands. The average annual potential evaporation is about 1800 mm (equivalent to about twice the average annual rainfall) and is exceeded by rainfall only during the months of May through to, and including, August. The mean maximum temperature ranges between 17°C and 30°C, with the hottest months being January and February. The mean minimum temperature ranges between 9°C and 18°C, with the coldest months being July and August.

Figure 4 shows rainfall records for the Perth Region between 1876 and 2002. The annual rainfall had a rising trend to the 1930s and a decline thereafter, with rainfall since about 1968 being below average. Figure 4 also shows that short-term cycles occur, during which the annual rainfall is mostly above or mostly below the long-term average for several successive years. The decreasing trend in average rainfall currently being experienced is probably, therefore, part of a longer term cycle that may show an increasing trend in the future.

2.3 Geomorphology

Darling Plateau. The Darling Plateau is capped with laterite that has formed over weathered Precambrian crystalline rocks. The plateau has a regional average elevation of about 350 m AHD (Australian Height Datum) and, in the Perth Region, is dissected by seven major rivers and numerous streams. The plateau is bounded to the west by the Darling Scarp, which follows the Darling Fault (Playford and Low, 1972; Playford et al., 1976). Coastal cliffs were formed along sections of the Darling Scarp during the Late Tertiary or early Pleistocene.

Dandaragan Plateau. The Dandaragan Plateau is a sand- and laterite-covered plateau overlying Cretaceous sediments of the Perth Basin. It has a regional average elevation of about 250 m AHD and is generally gently undulating. The Quaternary sand cover of the plateau is unrelated to the sand of the coastal plain, is thin (commonly less than 10 m thick) and derived from the underlying Cretaceous sediments. Many brooks and streams rise on the plateau and flow in a westerly direction onto the coastal plain. The Dandaragan Plateau is bounded to the west by the Dandaragan and Gingin Scarps which resulted from fluvial and marine erosion in the Late Tertiary or early Pleistocene and are not fault controlled as is the Darling Scarp.

Swan Coastal Plain. The Swan Coastal Plain in the Perth Region is about 36 km wide in the north and some 23 km wide in the south and is bounded to the east by the Gingin and Darling Scarps, which rise steeply to more than 200 m above sea level (Fig. 5). The scarps represent the eastern boundary of marine erosion that occurred during the Tertiary and Quaternary. The Swan Coastal Plain consists of a series of distinct landforms (McArthur and Bettenay, 1960), roughly parallel to the coast and closely associated with the surface geology (Fig. 6). The most easterly landform comprises the colluvial slopes that form the foothills of the Darling and Dandaragan Plateaus and which represent dissected remnants of a sand-covered, wave-cut platform known as the Ridge Hill Shelf. West of, and at the base of, the colluvial slopes, the Pinjarra Plain is a piedmont and valley-flat alluvial plain consisting predominantly of clayey alluvium that has been transported by rivers and streams down from the Darling and Dandaragan Plateaus. The plain is generally about five kilometres wide adjacent to the colluvial slopes, but along the Serpentine River it is about 15 km wide in an east-west direction.

West of the Pinjarra Plain, the Bassendean Dune system forms a gently undulating eolian sandplain about 20 km wide with the dunes to the north of Perth generally having greater topographic relief than those to the south. The dunes probably accumulated as shoreline deposits and coastal dunes during interglacial periods of high sea level and originally consisted of mostly lime sand with quartz sand and minor fine-grained black heavy mineral concentrations. Apart from a small local area to the south of Perth, the carbonate material has been completely leached, leaving dunes consisting entirely of quartz sand.

West of the Bassendean Dune system are two systems of dunes that fringe the coastline. The most easterly of these is the Spearwood Dune system which consists of slightly calcareous eolian sand, remnant from leaching of the underlying limestone. The most westerly dune system that flanks the ocean is the Quindalup Dune system consisting of wind-blown lime and quartz beach-sand forming dunes or ridges generally oriented parallel to the present coast, but may also occupy blowouts within the Spearwood Dune system.

The ephemeral rivers that cross the coastal plain are flanked by clayey floodplains and river terraces of recent origin. Other wetlands, consisting of swamps and lakes, have formed in the interdunal swales of the Bassendean Dune system and in the interbarrier depressions between the Spearwood Dune and Bassendean Dune systems and within the Spearwood Dune system.

South of Perth, the coastal plain has a maximum elevation of about 75 m AHD but has an average elevation of only about 25 m AHD. To the north of Perth the land surface of the coastal plain rises gradually from the coast to an elevation of about 100 m AHD (Fig. 5) but is generally more undulating along the coastal strip of the Quindalup Dune and Spearwood Dune systems.

2.4 Wetlands

Wetlands of the Perth Region have been defined as ‘areas of seasonally, intermittently or permanently waterlogged soils or inundated land, whether natural or otherwise, fresh or saline; e.g. waterlogged soils, ponds, billabongs, lakes, swamps, tidal flats, estuaries, rivers and their tributaries’ (Wetlands Advisory Committee, 1977).

2.4.1 Drainages

Eight major drainages cross the area (Fig. 1). From north to south, they are Moore River, Gingin Brook, Swan River, Canning River, Serpentine River, North Dandalup River, South Dandalup River and Murray River. Except for Gingin Brook, which rises on the Dandaragan Plateau, each has its headwaters on the Darling Plateau. Runoff results from rainfall on the plateau and land adjacent to the rivers on the coastal plain and, together with groundwater discharge, contributes to flow within the rivers. The major tributaries, Ellen Brook, Helena River and Southern River also carry runoff from the Darling Plateau, although Ellen Brook and Southern River mainly carry groundwater discharge.

Most of the major drainages are perennial and have greater flows during the rainy winter months than during summer, when the flow is mainly from groundwater discharge. Many of the smaller drainages, most of which are ephemeral and dissipate on the coastal plain, originate on the Dandaragan and Darling Plateaus. Those that have base levels above the watertable contribute to groundwater recharge and are losing streams. Others, such as the major drainages and tributaries that cross the coastal plain, generally have base levels above the watertable in the east and are losing streams in these areas. To the west, the base levels of the major drainages are mostly below the watertable and, in these areas, they become gaining streams and sites of groundwater discharge. Depending on climatic conditions and variations in watertable elevations, different sections of the drainages may be losing streams during some periods of the year and gaining streams during other periods. Groundwater also discharges into numerous, naturally occurring and constructed drains that are connected to the major drainages and to some of the lakes.

2.4.2 Lakes and swamps

The lakes of the coastal plain can be classified according to their age, origin and topographic location (Allen, 1981a). The old lakes lie along the eastern margin of the coastal plain, at the contact between the Pinjarra Plain and the Bassendean Dunes, and the young lakes along the western margin of the plain within the interdunal depressions of the Quindalup and Spearwood Dunes.

All lakes occupy shallow depressions in the land surface. Along the coastal belt of limestone, some lakes occur in dolines, particularly in areas where the land surface is karstic. Elsewhere, the lakes occur in interdunal and interbarrier depressions. Some lakes and most of the swamps exist in swales in otherwise flat terrain. Many of the lakes are surrounded by vegetation and are commonly bordered with reeds and sedges. They all contain sediments of biogenic origin consisting of peat, peaty sand, diatomite, calcareous clay (boglime) and freshwater marly limestone. The lacustrine sediments on the up groundwater-flow side of the lakes are generally more sandy than those on the down groundwater-flow side, which are commonly peaty.

Most of the lakes of the Swan Coastal Plain are shallow and range in depth from about 0.5 to three metres. Exceptions are Lake Richmond in the Rockingham area, which is about 10 m deep, and some of the lakes that occur in dolines of the coastal limestone belt, such as Lake Nowergup, which is about five metres deep.

Water in some lakes, for example Yeal Swamp and Lake Mariginiup, is temporarily perched above the peaty lacustrine sediments only during periods of exceptionally high rainfall. Following rain, hydraulic connection between lakewater and groundwater is rapidly obtained and the lakewater levels quickly represent the isopotential levels of the groundwater system connected to the lake (Allen, 1980; Davidson, 1983; Hall, 1985; Townley et al., 1993). During summer, because of declining groundwater levels and lack of rainfall, many of the very shallow lakes become dry. Along the coastal limestone belt, the maximum water level in some of the lakes is believed to be controlled by cavernous limestone that acts as spillways; however, this phenomenon has not been verified.

The swamps of the coastal plain, by definition, are sumplands and damplands, are seasonally waterlogged or inundated and contain water usually only during the winter months. Many of the swamps are temporarily perched for short periods above the watertable and downward leakage of water is inhibited by peaty swamp deposits and in some areas, particularly south of Perth, by a ferruginous hardpan, colloquially called ‘coffee rock’.

Both lakes and swamps are evaporative basins and, as a consequence, the salinity of the contained water varies greatly depending mainly on evaporative losses and also the groundwater flow system associated with the wetland. Some lakes and swamps are not associated with groundwater outflow; they are groundwater sinks and are saline to hypersaline (e.g. Lake Walyungup). The salinity of water in the lakes and swamps also varies seasonally, being freshest at the end of winter and most saline towards the end of summer. After heavy rainfall, this more saline water is flushed downwards into the groundwater to form a brackish plume down hydraulic gradient from the lakes and swamps.

Lakes are important habitats for many species of plants and animals and, because of their environmental significance, have been extensively investigated from a hydrogeological perspective by GSWA, the former Water Authority, and the CSIRO Division of Water Resources. With respect to groundwater flow, there are four major types of lakes (Fig. 7) within the Perth Region.

- Perched lakes: There are no permanent, truly perched lakes on the Swan Coastal Plain. However, some wetlands, possibly Yeal Swamp for example, appears to be perched above the watertable by clayey sediments, peaty lacustrine deposits or, particularly in the southern Perth Region, by ‘coffee-rock’ (iron-oxide cemented sand). Most of these lakes are only temporarily perched and become dry during the summer because of evaporation and some downward leakage to the watertable. Others that are hydraulically connected to the watertable during winter may hold perched water temporarily during summer when the watertable declines to a depth beneath the base of the lakes. On the coastal plain, temporary perching most commonly occurs where the watertable is less than three metres below ground level and 'coffee rock' is at a shallower depth or is exposed at the surface. On the Dandaragan Plateau, temporary lakes are perched on a laterite hardpan at an elevation of more than 50 m above the watertable.

- Groundwater recharge lakes: These lakes generally occur high in the landscape where the watertable is greater than two metres below ground level. When the watertable rises into the bed of the lake, the lake may become a groundwater discharge lake or a groundwater throughflow lake. Many are within the sandy sediments of the Bassendean Sand and, since very little rainfall runoff occurs within the Bassendean Dune system, the groundwater recharge catchment area of these lakes is limited mostly to the surface area and immediate surrounds of the lakes. Stormwater and compensating basins that receive stormwater runoff may be classified as groundwater recharge lakes.

- Groundwater discharge lakes: These lakes occur close to the coast, where they form groundwater discharge sinks within the surrounding watertable (e.g. Lakes Cooloongup and Walyungup). Because they are groundwater sinks and are not seasonally flushed by rainfall or groundwater throughflow, the lakewater is commonly hypersaline due to evaporative concentration of the dissolved salts. Those lakes that periodically become groundwater throughflow lakes (e.g. Lake Coogee) may be seasonally flushed and contain brackish to saline water.

- Groundwater throughflow lakes: These lakes occur throughout the coastal plain of the Perth Region and are by far the most common type of lake. The relationship between some of these lakes and the groundwater flow system has been investigated by Allen (1980), Davidson (1983), Hall (1985) and Townley et al. (1993).

These investigations have shown that the elevation of the watertable on the up-hydraulic gradient side of groundwater throughflow lakes is marginally higher than that of the lake surface, resulting in discharge of groundwater into the lake. The water in these lakes is maintained by this groundwater inflow, together with rain falling on the lake surface. On the down-hydraulic gradient side of these lakes, the elevation of the watertable is lower than the lake water level resulting in some outflow from the lake to the superficial aquifer (e.g. Lake Jandabup). The seasonal fluctuations in lake water levels are in phase with variations in watertable levels, but the response in the lake is usually greater for periods of heavy rainfall or higher evapotranspiration (evaporation from the free-standing water plus transpiration from the vegetation). The depth of the groundwater capture zone of these lakes depends mostly on the width of the lake in the direction of groundwater flow and also on the anisotropy of the aquifer. The width of the groundwater capture zone, normal to the groundwater flow direction, is commonly about twice the length of the lake in the same direction (Townley et al., 1993).

The previous investigations have shown that most of the aquifer thickness within the groundwater capture zone contributes groundwater discharge to the lakes. Also, of the accumulated groundwater outflow and rainfall to the lakes, about 90 per cent is lost to evapotranspiration. Consequently, the salinity of the lake water is higher than that of the discharging groundwater and a plume of more saline groundwater results at the outflow side of the lake.

3 Geology

3.1 Setting

The Perth Region is situated on the central part of the eastern onshore margin of the Perth Basin and overlies the southern end of the Dandaragan Trough, which is a major structural subdivision within the basin. Geophysical data show that sediments of the Perth Basin, in the Perth region, are about 12 000 m thick (Playford et al., 1976) and are separated from the crystalline rocks of the Yilgarn Craton by the Darling Fault. They have been gently folded in the northern area to form the Yanchep Syncline (west), Pinjar Anticline (central) and Swan Syncline (east, Fig. 8).

The major structural event in the Perth Region took place in the Neocomian, when rifting was terminated by the breakup of the Indian and Australian plates and the onset of seafloor spreading. During breakup, a period of widespread uplift and erosion produced the intra-Neocomian breakup unconformity (Fig. 9). By the end of the Neocomian, the present form of the Dandaragan Trough had been established.

In the Perth Region, folding and faulting in the Dandaragan Trough resulted in low dips to the north-east in the Yarragadee and Parmelia Formations. Offshore from Perth, the effects of breakup are much greater, with the development of a number of synclines and faulted anticlines (Davidson and Mory, 1990, Fig. 8). The Darling Fault is the most significant structural feature within the Perth Basin. It is a high-angle fault, dipping to the west, and is at least 1000 km long in a northerly direction. Major movement of the fault ended prior to the intra-Neocomian breakup unconformity (Playford et al., 1976, Fig. 9). The Warradarge, Lesueur, Beagle and Badammina Faults in the north-west, the Muchea Fault in the north-east and the Serpentine Fault in the south-east are also high-angle, normal faults predating the break-up unconformity (Fig. 8). However, some minor movement of the faults may have continued into the Early Cretaceous South Perth Shale and Mariginiup Member of the Leederville Formation.

The succeeding Cretaceous sediments that unconformably overlie the Neocomian unconformity surface are gently folded as a result of penecontemporaneous subsidence, differential compaction of the pre-existing sediments, and draping over fault blocks. As a consequence, the Swan and Yanchep Synclines have developed and there has been local non-deposition of the Gage Formation and the South Perth Shale over the Pinjar Anticline and in the south-eastern area. This has resulted in substantial variations in thickness of the post-break-up units (Fig. 10).

Over most of the Swan Coastal Plain, the Cretaceous sediments are concealed below a veneer of late Tertiary-Quaternary sediments up to about 100 m thick. However, on the Dandaragan Plateau, between the Gingin Scarp and the Darling Fault, Cretaceous sediments outcrop in some of the valleys and deeply incised drainages. Elsewhere, they are concealed by a thin (commonly only 3 m thick) cover of mostly Tertiary lateritised sediments and Quaternary eolian and alluvial sediments.

Without more detailed geological mapping, including investigation drilling, outcrop areas of Cretaceous sediments have been poorly delineated and only approximated on the geological maps.

The Kings Park Formation is a flat-lying, shallow-marine to estuarine deposit laid down in a drowned river valley (Playford et al., 1976) that eroded to a depth of about 550 m below sea level and into the Jurassic Yarragadee Formation. The Rockingham Sand occupies a channel eroded into the Cretaceous Leederville Formation to a depth of about 100 m below sea level. The sediment is probably a nearshore fluvial or marine deposit. The superficial formations are flat lying and rest unconformably on the eroded surface of pre-existing formations. They were deposited during eustatic changes in sea level during the late Tertiary-Quaternary (Allen, 1981a,b).

3.2 Stratigraphic units

The stratigraphic information was obtained by interpreting geophysical logs and palynology from deep investigation and production bores (Fig.11). Davidson (1995) used information from 105 bores that include mainly artesian monitoring bores (AM series), Water Corporation production bores and offshore petroleum exploration bores. The stratigraphic units of the Perth Region were described therein in order of deposition.

This study uses information from 188 bores (Table 1) that combines all the bore information in Davidson (1995), the Gillingarra and Moora Line exploration bores, recent Water Corporation and private production bores, and selected recent investigation bores. The stratigraphic units are described in order of increasing age.

3.2.1 Superficial formations

The ‘superficial formations’ is a collective and informal name for sediments of Quaternary age on the Swan Coastal Plain (Allen, 1976). The term embraces Safety Bay Sand, Becher Sand, Tamala Limestone, Bassendean Sand, Gnangara Sand, Guildford Clay, Yoganup Formation and Ascot Formation. These formations consist of up to 90 m laterally and vertically variable sequences of sand, limestone, silt, and clay. Near the coast, the sediments consist of calcareous marine sands and eolianites or coastal limestone (Tamala Limestone and Safety Bay Sand). Inland, they consist of variable sequences of fine and medium sand with minor silt and limestone (mainly Bassendean Sand) that interfinger with a sequence of clay and clayey sand towards the foothills of the Gingin and Darling Scarps (Guildford Clay). The Guildford Clay has also been deposited along river valleys.

On the Dandaragan Plateau there is a very thin cover (< 10 m) of Tertiary lateritised sediments and Quaternary eolian and alluvial sediments. They are reworked Cretaceous sediments and unassociated with those superficial formations on the Swan Coastal Plain. The sediments are unsaturated and negligible in the context of this study.

Along the Gingin Scarp, the superficial formations unconformably overlie the Leederville and/or Parmelia Formations (Fig. 10). The Poison Hill Greensand, Gingin Chalk, Molecap Greensand, and Osborne Formation have been eroded out, or not deposited, prior to the deposition of the Quaternary sediments (URS, 2002a,b).

Safety Bay Sand

The Safety Bay Sand consists of white, unlithified, calcareous fine- to medium-grained quartz sand and shell fragments, but predominantly medium-grained with traces of fine-grained, black, heavy minerals (Passmore, 1967, 1970). The Safety Bay Sand is up to 24 m thick, lies along the coastal margin as beach sand and eolian stable and mobile dunes (Quindalup Dune System of McArthur and Bettenay, 1960), and unconformably overlies the Becher Sand and Tamala Limestone (Fig. 12).

Becher Sand

The Becher Sand, which extends along the coastal margin, consists of fine- to medium-grained quartz and skeletal sand that is mostly structureless and bioturbated. The Becher Sand contains lenses of silty calcareous clay, rich in shell fragments.

The Becher Sand is of near-shore marine origin and underlies the Safety Bay Sand. Although it has not been investigated extensively, the Becher Sand has a maximum known thickness of 20 m in the Rockingham area but, elsewhere, it is generally 10 to 15 m thick (Semeniuk and Searle, 1985). It unconformably overlies the Tamala Limestone.

Tamala Limestone

The Tamala Limestone occurs along the coastal strip and consists of creamy-white to creamy-yellow, locally light grey, calcareous eolianite (Playford et al., 1976). The Tamala Limestone contains variable proportions of quartz sand, fine- to medium-grained shell fragments and minor clayey lenses. The quartz sand is generally fine- to coarse-grained, but predominantly medium-grained, moderately sorted, subangular to rounded, frosted and commonly stained with limonite. At the base of the Tamala Limestone, glauconite and phosphatic nodules, derived from the Molecap Greensand, are present locally. The limestone contains numerous solution channels and cavities, particularly in the zone where the watertable fluctuates, and in some areas has karst structures. Locally, the limestone may be almost impermeable, being tightly cemented with a siliceous cement.

Along the coastal strip, the Tamala Limestone varies in thickness depending mainly on topography, although it is known to have a maximum thickness of about 110 m. Depending on location, this unit unconformably overlies either the Bassendean Sand, Lancelin Formation, Osborne Formation, or Leederville Formation. Along the coastal margin it is unconformably overlain by the Safety Bay Sand or Becher Sand (Fig. 12).

Its exposed and leached upper surface is coincident with the eolian Spearwood Dune System of McArthur and Bettenay (1960).

Bassendean Sand

The Bassendean Sand covers most of the central Perth Region (Playford and Low, 1972). It consists of leached pale grey to white, fine- to coarse-grained but predominantly medium-grained, moderately sorted, subrounded to rounded quartz sand, and commonly has an upward fining progression in grain size. In the southern Perth area, local remnant calcareous facies of the Bassendean Sand remain unleached. Fine-grained, black, heavy minerals are generally scattered throughout the formation but are locally more concentrated in thin layers, probably representing a shallow-marine origin of sedimentation. A layer of friable, mostly weakly limonite-cemented sand, colloquially called 'coffee rock', extends throughout most of the area at about the watertable. In the Jandakot area, the 'coffee rock' is generally thicker than elsewhere.

The Bassendean Sand varies in thickness, depending mainly on the topography, and has a maximum known thickness of about 80 m. The Bassendean Sand unconformably overlies the Tertiary and Cretaceous sediments. This unit interfingers to the east with the Guildford Clay and conformably overlies the Gnangara Sand. To the west, it is unconformably overlain by the Tamala Limestone (Fig. 12). The exposed surface of the Bassendean Sand is coincident with the eolian Bassendean Dune system of McArthur and Bettenay (1960). The interfingering stratigraphic relationships of the Bassendean Sand with the Gnangara Sand and Guildford Clay indicate that the formation was deposited under a changing, and at times alternating, fluvial, estuarine and shallow-marine environment.

Gnangara Sand

The Gnangara Sand of Morgan (1964) and Davidson (1995) consists of pale grey, fine- to very coarse-grained, very poorly sorted, subrounded to rounded quartz sand and abundant feldspar. At some localities it is apparently of bimodal origin, being both fine-grained and very coarse-grained. This unit is predominantly of fluvial origin, but in those areas containing bimodal sediments it is probably estuarine.

The Gnangara Sand extends over most of the central Perth Region and is readily identifiable from drillhole cuttings by the common occurrence of well-rounded very coarse grains, subangular fine to medium grains and feldspar. It has a maximum known thickness of about 30 m.

The Gnangara Sand is a basal sand that interfingers with the Guildford Clay to the east (Fig. 12). It rests unconformably on the Ascot Formation, Kings Park Formation and Cretaceous and Jurassic sediments, and is conformably overlain by the Bassendean Sand. To the west it is unconformably overlain by the Tamala Limestone.

Guildford Clay

The Guildford Clay was originally defined by Aurousseau and Budge (1921) as the ‘Guildford Clays’ and the name was revised by Low (1971) to ‘Guildford Formation’. However, the name Guildford Clay has persisted and is commonly used, particularly for areas where it outcrops (Fig. 6). For this reason, the name Guildford Clay was reinstated (Davidson, 1995) and refers to the clayey sediments originally described by Aurousseau and Budge (1921) for the type area in the Swan River valley around Guildford.

The Guildford Clay consists of pale grey, blue, but mostly brown, silty and slightly sandy clay, which interfingers to the west with the Bassendean Sand and Gnangara Sand. It is up to 35 m thick and commonly contains lenses of fine- to coarse-grained, very poorly sorted conglomeratic and sometimes shelly sand at its base, particularly in the Swan Valley area. These basal lenses are probably remnant deposits of the Yoganup Formation or the Ascot Formation, which is thought to be a lateral equivalent of the Yoganup Formation (Baxter and Hamilton, 1981) and occurs sporadically along the eastern margin of the coastal plain (Fig. 6). These sand lenses provide local sources of groundwater for privately owned supplies.

The Guildford Clay is predominantly of fluvial origin and is restricted mainly to the areas of its outcrop, but it may also exist locally in areas removed from present drainages, such as at Menora, north of Perth, and Fremantle, to the south-west of Perth. To the south of Perth, in the Ferndale-Lynwood area, a widespread, thick, black, silty clay, possibly of lacustrine or fluvial origin, is probably a lateral equivalent of the Guildford Clay.

The Guildford Clay unconformably overlies the Yoganup Formation, Ascot Formation, Kings Park Formation, and Cretaceous and Jurassic sediments, and crops out over much of the eastern Perth Region (Fig. 6), where it forms the Pinjarra Plain of McArthur and Bettenay (1960).

Yoganup Formation

The Yoganup Formation occurs sporadically along the eastern margin of the Perth Region (Fig. 6) and extends, beneath ground level, westwards about five kilometres from the foothills of the Darling Scarp (Low, 1971). The formation consists of white to yellowish-brown, unconsolidated, poorly sorted sand, gravel and pebbles with occasional subordinate clay, ferruginised grains and common heavy minerals. The Yoganup Formation occurs at the base of the superficial formations where it may interfinger with the Ascot Formation (Fig. 12).

In the Perth Region, it has a maximum known thickness of about 10 m and has been extensively eroded prior to the deposition of the Guildford Clay. It is a shoreline deposit representing a buried prograding coastline of dunes, beach ridges and deltaic deposits (Baxter, 1982). The Yoganup Formation unconformably overlies the

Osborne Formation or the Leederville Formation and it is unconformably overlain by the Guildford Clay.

Ascot Formation

The Ascot Formation of Cockbain and Hocking (1989), including the Jandakot Beds, consists of hard to friable, grey to fawn calcarenite with thinly interbedded sand commonly containing shell fragments, glauconite and phosphatic nodules near the base of the formation. The sand is fine- to coarse-grained, very poorly sorted, angular to rounded, with a rich assemblage of bivalves and gastropods. To the south of Perth thick beds of shelly, silty clay, and thinly bedded glauconitic clay occurs in places near the base of the formation.

The Ascot Formation represents a sequence of depositional events along the neritic margins of a progressively prograding shoreline (Kendrick et al., 1991). It has a maximum thickness of about 30 m in the northern Perth area and is up to 20 m thick south of Perth, and is known to occur over wide areas at the base of the superficial formations (Fig. 12). The Ascot Formation lies unconformably on the Poison Hill Greensand, Molecap Greensand, Osborne Formation or Leederville Formation, except where the formation has been eroded out or was not deposited prior to the deposition of the Quaternary sediments.

3.2.2 Rockingham Sand

The Rockingham Sand, defined by Passmore (1967, 1970), consists of brown to pale grey, slightly silty, slightly felspathic, medium- to coarse-grained subangular sand. It is unconformably overlain by the superficial formations (Fig. 13) and it occupies an eroded valley incised into the Wanneroo Member of the Leederville Formation (Fig. 14). The Rockingham Sand has been considered to be of shallow-marine origin and is known to occur onshore only in the Rockingham area, where it has a maximum thickness of about 80 m (Fig. 15). Offshore, it is found beneath the southern end of Garden Island. The age of the Rockingham Sand is uncertain, but is probably Pliocene.

3.2.3 Kings Park Formation

The Kings Park Formation occupies a deep, eroded valley incised through the Cretaceous sequence of sediments into the Jurassic sediments (Fig. 16). This formation consists predominantly of grey, calcareous, glauconitic siltstone and shale of shallow-marine to estuarine origin. The valley occupied by the Kings Park Formation may once have connected with the Perth Canyon, which now cuts the continental slope west of Rottnest Island (Playford et al., 1976).

Two sandstone sequences that individually form the Kings Park aquifers, the Mullaloo Sandstone Member and Como Sandstone Member, lie within the formation and these may occupy secondary channels eroded into the shaly sequence at the top and near the base of the formation, respectively. Other unidentified channels containing sandy facies of the Kings Park Formation may also exist at different depths.

The Kings Park Formation unconformably overlies the Cretaceous and Jurassic sediments (Fig. 16) and is unconformably overlain by the superficial formations. It has a maximum onshore thickness of about 520 m in the Claremont area west of Perth and is of Paleocene to Eocene age (Playford et al., 1976).

Mullaloo Sandstone Member

The Mullaloo Sandstone Member, which lies at or near the top of the Kings Park Formation, consists of poorly sorted, fine- to very coarse-grained, pale brownish-green, slightly glauconitic and clayey sand. The member has an onshore maximum thickness of about 170 m and occupies fluvial channels incised into the siltstone and shale of the Kings Park Formation (Fig. 17).

The distribution of the Mullaloo Sandstone is poorly understood owing to lack of data. It is possible that some thin overflow sedimentation of the Mullaloo Sandstone Member may have occurred adjacent to, and overlapping, these channels, but this is not shown on Figure 13. For example, a bore, approximately 500 m south-west of the southern boundary of the Mullaloo Sandstone Member and adjacent to the north-western bank of the Swan River, in the Nedlands area, intersected about five metres of clayey sand, possibly belonging to the Mullaloo Sandstone Member.

Como Sandstone Member

The Como Sandstone Member consists of fine- to coarse- but predominantly medium-grained, moderately sorted, subangular to subrounded, pale grey to pale greenish-grey, slightly clayey sand. It probably occupies a fluvial channel of limited extent near the base of the Kings Park Formation.

The Como Sandstone Member was intersected in only two of the artesian monitoring bores (AM32 and AM40, Table 1). Onshore, it has a maximum known thickness of 57 m, recorded from AM40 borehole.

3.2.4 Lancelin Formation

The Lancelin Formation occurs in the Guilderton area where it consists of a white to greenish-brown, glauconitic marl and thin chalky beds. Beneath the chalky beds, a non-calcareous mudstone unit, atypical of the marl of the Lancelin Formation, may represent a fine-grained facies equivalent of the Molecap Greensand. Until more palynological work is carried out on this fine-grained unit, it has been assigned to the Lancelin Formation and not Molecap Greensand as in Davidson (1995).

The top of the Lancelin Formation is an erosion surface, unconformably overlain by the Tertiary Kings Park Formation or the younger superficial formations (Fig. 18). It is unconformably underlain by the Kardinya Shale Member of the Osborne Formation or, in limited areas, by the Pinjar Member of the Leederville Formation (Fig. 19). The formation is of Coniacian to late Maastrichtian age, based on palynological and microfossil data (Backhouse, 1986; Rexilius, 1984), and may extend into the Turonian, to be a facies equivalent of the Molecap Greensand.

The Lancelin Formation is of marine origin and, within the Perth Region, has a maximum onshore thickness of about 140 m (Fig. 20).

3.2.5 Poison Hill Greensand

The Poison Hill Greensand consists of unconsolidated pale yellowish-green to dark green, fine- to very coarse-grained, very poorly sorted, commonly rounded and spherical, richly glauconitic, silty and locally clayey sand. The sand is similar in lithology and characteristics to that of the Henley Sandstone Member, although it is generally less silty and less clayey, and the sand grains are better rounded and more spherical than those of the Henley Sandstone Member. In the Mirrabooka area, the upper 50 m of the Poison Hill Greensand consists of fine- to medium-grained, moderately sorted, slightly clayey, pale green sand. This sand, now referred to as the Poison Hill Greensand, was originally thought to be of Quaternary age and a channel infill deposit (Morgan, 1964; Allen, 1977; Barnes, 1977). However, extensive sampling for palynological examination has not been able to confirm this. Further sampling within the Mirrabooka area may show that this sandy unit is Tertiary in age and possibly belongs to a sandstone member of the Kings Park Formation.

Structure contours on the top of the Poison Hill Greensand are shown on Figure 21. The Poison Hill Greensand conformably overlies the Molecap Greensand or the Gingin Chalk (Fig. 22) and is unconformably overlain by the superficial formations. The Poison Hill Greensand occurs on the eastern margin of the study area, predominantly on the Dandaragan Plateau, and in the Wanneroo area of the Swan Coastal Plain. It has a maximum onshore thickness of about 60 m (Fig. 23).

3.2.6 Gingin Chalk

The Gingin Chalk is of Santonian to Campanian age (Cockbain, 1990). It is of shallow-marine origin and consists of weakly to moderately consolidated, pale grey to whitish-green, slightly glauconitic chalk, containing very thin beds of green sand in the Swan Syncline. In the northern Perth area, the chalk facies is very minor or absent, and the sand facies is difficult to distinguish from the sandy beds of the underlying Molecap Greensand. Correlation across this area has been interpreted from geophysical wireline logs and, without palynological data, is subject to modification.

Structure contours on top of the Gingin Chalk (Fig. 24), together with surface topographic contours (Fig. 5), show that the formation occurs at depths ranging from near ground level to about 110 m. It is conformably overlain by the Poison Hill

Greensand. The Gingin Chalk unconformably overlies the Leederville Formation (Pinjar Member) and the Osborne Formation (Kardinya Shale Member) and it conformably (or with a hiatus) overlies the Molecap Greensand (Fig. 25). It was originally thought to interfinger with the Lancelin Formation in the Guilderton area, although these chalky lenses are now believed to be a facies variation of the Lancelin Formation and not Gingin Chalk.

Gingin Chalk is present on the eastern margin of the study area, predominantly on the Dandaragan Plateau where it crops out in Gingin, and in the Wanneroo area of the Swan Coastal Plain. The unit has a maximum onshore thickness of about 40 m (Fig. 26).

3.2.7 Molecap Greensand

The Molecap Greensand is of Turonian to Santonian age. It occurs in the Swan Syncline and in the Wanneroo area, where it consists of fine- to medium-grained, yellowish-brown to greenish-grey, glauconitic, silty, and locally clayey sandstone. Phosphatic nodules are commonly present in the upper part of the formation. It was also thought to occur in the Yanchep Syncline, in the Guilderton area where its lithology is typically clayey. However, these sediments are now believed to belong to the Lancelin Formation.

The Molecap Greensand is conformably overlain by the Gingin Chalk, or in places a hiatus may exist and it is unconformably overlain by the Poison Hill Greensand or the superficial formations (Fig. 27). It overlies the Mirrabooka Member of the Osborne Formation, mostly with a transitional and conformable contact (Fig. 28) but in some areas there may be a hiatus between the Molecap Greensand and the Osborne Formation.

The Molecap Greensand is of shallow-marine origin and the contours on the top of the formation (Fig. 27), together with surface topographic contours (Fig. 5), show that it exists at depths ranging from ground level to about 120 m. With further drilling and palynological evidence the extent of the Molecap Greensand, and that of the Mirrabooka Member of the Osborne Formation, may be modified. The Molecap Greensand is mostly unconsolidated and has a maximum thickness of about 60 m (Fig. 29).

3.2.8 Osborne Formation

The Osborne Formation consists of three members: an upper interbedded sandstone, siltstone and shale sequence (Mirrabooka Member); a middle shale sequence (Kardinya Shale Member); and a basal sandy sequence (Henley Sandstone Member). The Osborne Formation is conformably and unconformably overlain by the Molecap Greensand, and unconformably overlain by the Gingin Chalk, Lancelin Formation, or the superficial formations on an erosion surface. Structure contours on top of the Osborne Formation are given in Figure 30. The formation unconformably overlies the Pinjar Member or the Wanneroo Member of the Leederville Formation (Fig. 31). Beneath the Perth Region and within the Swan Syncline it has a maximum thickness of about 180 m (Fig. 32) and ranges in age from Aptian to Turonian.

Mirrabooka Member

The Mirrabooka Member consists of sandstone with thin interbeds of siltstone and shale. The sandstone is weakly consolidated, dark greenish-brown, fine to very coarse-grained, very poorly sorted, silty and richly glauconitic. The siltstones and shales are moderately consolidated, dark green to black, glauconitic, and contain common spherical, coarse to gravel-sized quartz grains.

The Mirrabooka Member is a sandy unit in the uppermost section of the Osborne Formation. This member is conformably overlain by the Molecap Greensand. However, based on scarce biostratigraphic data, there may be a hiatus between the Mirrabooka Member and the Molecap Greensand. Elsewhere, the Mirrabooka Member is unconformably overlain, on an erosion surface, by the superficial formations (Fig. 33). It conformably overlies the Kardinya Shale Member (Fig. 34) and is of Albian to Cenomanian age, based on palynological data (Backhouse, 1980b).

The Mirrabooka Member occurs in the northern Perth area where it is difficult to distinguish from the overlying Molecap Greensand without palynological evidence. It has an onshore maximum thickness of about 140 m (Fig. 35).

Kardinya Shale Member

The Kardinya Shale Member of the Osborne Formation consists of moderately to tightly consolidated, interbedded siltstone and shale. These shales are dark green to black, commonly puggy and glauconitic, and contain thin interbeds of mostly fine-grained sandstone. Coarse grains with high sphericity are commonly scattered throughout the siltstone and shale.

The Kardinya Shale Member is a relatively thick siltstone-shale unit within the Osborne Formation. In the northern Perth area it is conformably overlain by the interbedded sandstone-shale sequence of the Mirrabooka Member and is unconformably overlain by the Molecap Greensand or the Gingin Chalk. In the southern area it is unconformably overlain, on an erosion surface, by the superficial formations (Fig. 36). It conformably overlies the Henley Sandstone Member, but in the south where the Henley Sandstone Member is absent, it unconformably overlies the Pinjar Member or Wanneroo Member of the Leederville Formation (Fig. 37). The Kardinya Shale Member is of Albian to Cenomanian age, based on palynological data (Backhouse, 1979).

The Kardinya Shale Member is present mainly beneath the Dandaragan Plateau and the central Perth Region where it is recognisable in geophysical wireline logs by its relatively high gamma radiation and low resistivity. It has a maximum thickness of about 260 m (Fig. 38).

Henley Sandstone Member

The Henley Sandstone Member consists of sandstone and minor siltstone. The sandstone is weakly consolidated to friable, fine- to coarse-grained, very poorly sorted and characteristically dark greenish-brown and glauconitic. Very coarse to gravel-sized, well-rounded grains with high sphericity are common.

The Henley Sandstone Member is a predominantly sandstone unit at the base of the Osborne Formation. Its upper contact with the Kardinya Shale Member of the Osborne Formation (Fig. 39) is mostly abrupt but may be gradational or may interfinger with the shale sequence. It unconformably overlies the Wanneroo Member or the Pinjar Member of the Leederville Formation (Fig. 40). The Henley Sandstone Member is of late Aptian to early Albian age, based on palynological data (Backhouse, 1981).

The Henley Sandstone Member occurs mainly on the Dandaragan Plateau, and in the central Perth area of the Swan Coastal Plain, where it has an onshore maximum thickness of about 80 m (Fig. 41).

3.2.9 Leederville Formation

The Leederville Formation consists predominantly of discontinuous, interbedded sandstones, siltstones and shales with some conglomerate to the east, near the Darling Scarp. The sandstone beds of the Leederville Formation are of variable thickness and are similar to those of the Yarragadee Formation, although they are generally individually thinner. The sand is fine- to coarse-grained, angular to subangular, and mainly poorly sorted. Pyrite and carbonaceous material are common in the non-marine facies of the formation and glauconite is common in the marine facies, particularly south of Perth. Thin calcareous- and pyritic-cemented beds of sand characterise the marine facies over most of the southern half of the Perth Region.

Individual sandstone beds are generally between six and 20 m thick, although locally, beds reach 60 m in thickness, particularly south of Perth. However, the areas with the thickest sandstone beds do not necessarily coincide with the areas of greatest formation thickness.

The Leederville Formation is unconformably overlain by the Osborne Formation (Henley Sandstone Member and Kardinya Shale Member), Molecap Greensand, Gingin Chalk or the superficial formations. In the Perth area, the Leederville Formation has been eroded prior to deposition of the Kings Park Formation. In the Rockingham area the Leederville Formation has been deeply eroded and is overlain by the Rockingham Sand. Structural contours on the top of the Leederville Formation (Fig. 42), together with surface topographic contours (Fig. 5), show that the formation ranges in depth from the surface to about 500 m. The Leederville Formation unconformably overlies the Cattamarra Coal Measures, Yarragadee Formation or the Parmelia Formation and conformably overlies the Gage Formation or the South Perth Shale with a transitional contact (Fig. 43).

The thicker sections of the Leederville Formation are found within the synclinal structures (Fig. 44), and the maximum thickness onshore is about 600 m, within the axis of the Yanchep Syncline to the east of Guilderton (Cockbain and Playford, 1973). North of Perth, in the axis of the Swan Syncline, the maximum thickness of the Leederville Formation is about 500 m, while over the Pinjar Anticline the minimum thickness is about 50 m. To the east, the formation overlaps the Darling Fault, which forms the approximate boundary between the sediments of the coastal plain and the crystalline rocks of the Yilgarn Craton.

The Leederville Formation comprises three distinct and mappable units (Pinjar Member, Wanneroo Member and Mariginiup Member) ranging in age from Aptian to Valanginian.

Pinjar Member

The Pinjar Member consists of discontinuous, interbedded sandstones, siltstones and shales of marine and non-marine origin, with individual sandstone beds about three to six metres thick. The sandstones are weakly consolidated, grey, fine- to very coarse-grained, poorly sorted, subangular to subrounded, and commonly silty. The siltstones and shales are dark grey to black, thinly laminated with fine-grained sandstone, commonly micaceous and, in the northern area, may contain lignitic fragments.

The Pinjar Member is the uppermost member of the Leederville Formation. It is unconformably overlain by the Osborne Formation (Henley Sandstone Member or Kardinya Shale Member), Molecap Greensand, Gingin Chalk or the superficial formations. Over the Pinjar Anticline, the Pinjar Member has been completely eroded prior to deposition of the superficial formations. Structure contours on the top of the Pinjar Member are shown in Figure 45 and, together with surface topographic contours (Fig. 5), indicate that the member occurs at depths ranging from ground level to about 400 m beneath ground level. The Pinjar Member is conformable on the Wanneroo Member (Fig. 46) and is of late Neocomian to Aptian age, based on palynological data (Backhouse, 1980a).

The Pinjar Member lies beneath most of the Perth Region and extends approximately 50 km north, beneath the coastal strip, to near Lancelin. It has a maximum onshore thickness of about 150 m within the Yanchep and Swan Synclines (Fig. 47).

Wanneroo Member

The Wanneroo Member consists of discontinuous interbedded sandstones, siltstones and shales of marine and non-marine origin. Individual sand beds range in thickness from less than 10 m to more than 20 m, but are generally between 12 and 15 m thick. The sandstone interbeds are weakly consolidated, pale grey, fine- to very-coarse grained (predominantly coarse), poorly sorted, angular to subangular, and slightly silty. The siltstones and shales are grey, slightly micaceous, and form beds of thickness similar to those of the sandstones. Along the south-eastern margin of the Perth Region, and in many areas adjacent to the Darling Fault, granitic scree boulders from the Darling Scarp are commonly found within the Wanneroo Member.

The Wanneroo Member is conformably overlain by the Pinjar Member and it is unconformably overlain by the Osborne Formation (Henley Sandstone Member or Kardinya Shale Member), Molecap Greensand, Kings Park Formation, Rockingham Sand or superficial formations. The structure contours on the top of the Wanneroo Member (Fig. 48), together with surface topographic contours (Fig. 5), show that the member lies at depths ranging from ground level to about 500 m beneath ground level. It conformably overlies the South Perth Shale or the transitional Mariginiup Member, and in places it unconformably overlies the Yarragadee Formation or Parmelia Formation (Fig. 49). The Wanneroo Member is of late Neocomian to Aptian age, based on palynological data (Backhouse, 1980a).

The Wanneroo Member extends beneath most of the Perth Region. It has an onshore maximum thickness of about 300 m within the Yanchep Syncline (Fig. 50). In the Jandakot area, south of Perth, the uppermost sandstone bed of the Wanneroo Member is generally thicker than the sandstone beds at greater depths and elsewhere within the Perth Region.

Mariginiup Member

The Mariginiup Member consists of thinly interbedded and discontinuous, grey to black, siltstones and shales with minor, generally less than one metre thick, very thin beds of mostly fine-grained sandstone. It is predominantly of marine origin, commonly glauconitic, micaceous and sometimes fossiliferous. It may be weakly to strongly cemented with a pyritic or calcareous cement. In the northern area, the Mariginiup Member is slightly more sandy and coarser grained than it is in the south.

The Mariginiup Member, the basal member of the Leederville Formation, represents the conformable transitional period of sedimentation between the South Perth Shale below and the Wanneroo Member above. It is conformably overlain by the Wanneroo Member or the Pinjar Member and in places is unconformably overlain by the superficial formations. The surface elevation of the Mariginiup Member (Fig. 51), together with land surface elevation (Fig. 5), show that the member occurs at depths ranging from ground level to about 800 m. It unconformably overlies the Cattamarra Coal Measures, Yarragadee Formation or the Parmelia Formations and conformably overlies the Gage Formation or the South Perth Shale (Fig. 52). The Mariginiup Member is of Valanginian to early Barremian age, based on palynological data (Backhouse, 1980a).

The Mariginiup Member lies beneath most of the Perth Region and extends north beneath the coastal strip to near Cataby, and beneath the Dandaragan Plateau to the Watheroo area. Onshore, the member has a maximum thickness of about 350 m within the Swan Syncline (Fig. 53).

3.2.10 South Perth Shale

The South Perth Shale is predominantly of shallow-marine origin and consists mainly of thinly interbedded, grey to black siltstone and shale with minor, thin, sandy beds and local, thin, calcareous beds. In the southern Perth Region, the South Perth Shale is commonly cemented, hard, and is pyritic and glauconitic. In the northern area it may be weakly cemented, though mostly it is uncemented and has a tendency to be squeezed by overburden pressure into uncased boreholes.

The South Perth Shale is overlain, with a conformable and transitional contact, by the Leederville Formation (Mariginiup Member and Wanneroo Member) and, near Perth, it is unconformably overlain by the Kings Park Formation. Structure contours on the top of the South Perth Shale (Fig. 54), together with surface topographic contours (Fig. 5), show that the formation lies at depths ranging from 60 to 850 m. The South Perth Shale unconformably overlies the Cattamarra Coal Measures, Yarragadee Formation or the Parmelia Formation and conformably overlies the Gage Formation (Fig. 55). The formation has an estimated maximum thickness of about 300 m (Fig. 56) and, like the Gage Formation, is better developed in the tectonically downthrown parts of the Perth Basin. The South Perth Shale is of Valanginian to Hauterivian age (Cockbain, 1990).

3.2.11 Gage Formation

The Gage Formation consists of interbedded sandstones, siltstones and shales, and can be mapped as occurring at the base of the Warnbro Group over a large area of the central onshore margin of the Perth Basin. The sandstone beds are of variable thickness (3–30 m) but are generally thickest in the overall thickest part of the formation. The beds consist of pale grey, fine- to coarse-grained sand similar to that of the Yarragadee Formation, from which they probably originated by erosion. The interbedded siltstones and shales are pale grey to grey-brown in colour, slightly micaceous and form beds generally less than six metres thick. Cumulatively, with the interbedded sandstones, these beds may form thick sections of mainly sandstone or mainly siltstone.

The Gage Formation is overlain, with a conformable and abrupt contact, by the South Perth Shale or the Leederville Formation (Mariginiup Member). Near Perth, it is unconformably overlain by the Kings Park Formation. Structure contours on the top of the Gage Formation (Fig. 57), together with surface topographic contours (Fig. 5), show that the formation occurs beneath ground level at depths ranging from 60 to 850 m. The Gage Formation was probably deposited in a paralic environment infilling structurally low areas on the intra-Neocomian erosion unconformity (Figs 9, 58). The formation unconformably overlies the Yarragadee Formation except in the south-west where it unconformably overlies the Cattamarra Coal Measures. It has an estimated maximum onshore thickness of about 300 m (Fig. 59). However, with further drilling and palynological examination, some strata currently identified as Gage Formation may be reinterpreted as Yarragadee Formation. The Gage Formation is of Valanginian to Hauterivian age (Cockbain, 1990).

3.2.12 Parmelia Formation

The Parmelia Formation, established by Backhouse (1984), is divided into an upper, predominantly shaley unit (possibly equivalent to the Carnac Member), a middle, more sandy unit (unofficial Parmelia Sand Member), and a basal shale unit (Otorowiri Member). Structure contours on top of the formation are given in Figure 60, which also shows the unconformable overlying strata. The Parmelia Formation is conformable on the Yarragadee Formation (Fig. 61) and has a maximum thickness of 750 m (Fig. 62). It is of Tithonian to Berriasian age (Backhouse, 1984). The Parmelia Formation is present on the Dandaragan Plateau and is bounded to the east by the Muchea and Darling Faults.

The thickness of the Parmelia Formation in some offshore areas is in excess of 1200 m. Crostella and Backhouse (2000) suggested that the formation in the offshore area be raised to group status. Within the group, the Otorowiri and Carnac Members are given formation status; the sandstone successions between the two units is also given formation status and named the Jervoise Sandstone.

The Parmelia Formation in the onshore area described here is a lateral equivalent of the Parmelia Group that is distributed extensively in the Perth offshore area.

Carnac Member

The Carnac Member of the Parmelia Formation consists of dark grey silty shale similar to that of the South Perth Shale. It is unconformably overlain by the Mariginiup Member, Wanneroo Member and Pinjar Member of the Leederville Formation (Fig. 63). The Carnac Member subcrops beneath the superficial formations in an area just north of Gingin Brook and extensively towards the northern boundary of the study area (Fig. 63). The shales of the Carnac Member grade gradually into the sandy facies of the Parmelia Formation and the boundary between the members is difficult to delineate. The Carnac Member is conformable above the Parmelia Sand Member of the Parmelia Formation (Fig. 64). It is extensive and has a maximum thickness of about 450 m (Fig. 65).

Parmelia Sand Member

The sandy facies of the Parmelia Formation has not been officially named and in this report it is referred to as the Parmelia Sand Member. It occupies the middle section of the Parmelia Formation, and has an upper gradational contact with the shales of the Carnac Member (Fig. 66). The Parmelia Sand Member is a lateral equivalent of the Jervoise Sandstone and is extensively distributed in the offshore area (Crostella and Backhouse, 2000). Structure contours on top of the Parmelia Sand Member are shown in Figure 66 and, together with surface topographic contours (Fig. 5), indicate that the member lies at depths ranging from ground level to about 850 m. However, without palynological data and from geophysical wireline logs alone, it is often difficult to distinguish from the other members of the Parmelia Formation. Its lower contact with the Otorowiri Member is more definite, although in some areas this may also be gradational and difficult to delineate (Fig. 67).

The Parmelia Sand Member consists of interbedded sandstones, siltstones and shales. In the Perth Region, the individual sandstone beds are variable in thickness but are generally only about five metres thick and consist of pale grey, fine- to very coarse-grained, predominantly medium-grained, subangular sand in a weak kaolinitic or siliceous cement. The member is believed to have a maximum thickness of about 750 m (Fig. 68), although without further drilling investigation this is difficult to verify. The sandstone beds are lithologically similar to those of the upper part of the Yarragadee Formation. The combined thickness of the shale beds, which are pale to dark grey, micaceous, carbonaceous and subfissile, approximates that of the sandstone beds (Backhouse, 1984).

Otorowiri Member

The Otorowiri Member, at the base of the Parmelia Formation, consists of interbedded siltstone and shale with very minor sandstone beds containing fine- to medium-grained clayey sand. The upper and lower surfaces of the Otorowiri Member are given in Figures 69 and 70 respectively, and the maximum thickness of 200 m is shown in Figure 71. The Otorowiri Member is a lateral equivalent of the Otorowiri Formation, and is continuously distributed in the offshore area (Crostella and Backhouse, 2000).

3.2.13 Yarragadee Formation

The Yarragadee Formation consists of laterally discontinuous interbedded sandstones, siltstones and shales and is more than 3000 m thick.

Within the Yanchep and Swan Synclines, the formation is non-marine and probably fluvial, with individual sandstone beds up to 30 m thick. These consist of pale grey, medium- to very coarse-grained, poorly sorted, slightly felspathic and weakly cemented sand. The siltstones and shales are of thickness similar to that of the sandstone beds and are commonly pyritic and micaceous (Allen, 1981a). Within the area of the Pinjar Anticline, and particularly beneath the Wanneroo area, the Yarragadee Formation was probably laid down in a shallow-marine or paralic environment. Here, the sandstones are of thickness similar to those elsewhere, but they are generally finer grained and better sorted. Thinly interbedded sandstones, siltstones and shales also occur throughout the entire thickness of the Yarragadee Formation.

The Yarragadee Formation extends beneath all of the coastal plain except in the south and south-east margin of the Perth Region, where it has been faulted and eroded out prior to the deposition of the Gage Formation, South Perth Shale, and Leederville Formation. In the north-eastern area, the Yarragadee Formation is conformably overlain by the Parmelia Formation (Backhouse, 1984) and elsewhere it is unconformably overlain by the Gage Formation, South Perth Shale or Leederville Formation (Mariginiup Member and Wanneroo Member). Near Perth, the upper section of the Yarragadee Formation and overlying Cretaceous units have been eroded prior to the deposition of the Kings Park Formation. Structure contours on the top of the Yarragadee Formation (Fig. 72), together with surface topographic contours (Fig. 5), show that the formation lies at depths greater than 800 m in the Yanchep Syncline, greater than 1000 m in the Swan Syncline, and at about 900 m in the Wanneroo area. The upper surface of the Yarragadee Formation gradually rises in a southerly direction from about 800 m depth in the Perth area to about 130 m depth in the southern part of the Perth Region. It also rises to the north, where it subcrops beneath the superficial formations (Fig. 72). The Yarragadee Formation is of Aalenian to Tithonian age (Cockbain, 1990).

Structure contours on the base of the Yarragadee Formation (Fig. 73) are poorly defined and can only be regarded as approximate. The isopach map of the Yarragadee Formation (Fig. 74) is also subjective but it shows that the formation has a maximum thickness of about 3500 m in the Swan Syncline.

3.2.14 Cadda Formation and Cattamarra Coal Measures

The Cadda Formation is a Middle Jurassic unit composed of marine deposits of shale, sandstone, and limestone (Commander, 1981). The formation is less than 50 m thick, and overlain by the Yarragadee Formation and underlain by the Cattamarra Coal Measures.

The Cattamarra Coal Measures consists of interbedded non-marine, probably fluvial, sandstones, siltstones and shales with minor coal seams, and may be more than 1500 m thick. In the Perth Region, the sandstones are pale grey in colour, often clayey, mostly medium- to coarse-grained and occur in beds up to 50 m thick. The siltstones and shales are dark grey, locally carbonaceous and commonly laminated, and form beds up to 30 m thick. The upper section of the formation is commonly weathered to a yellow, reddish-brown colour; the lower sections are locally cemented and hard.

The Cattamarra Coal Measures extends beneath most of the coastal plain, but at a relatively shallow depth only in the southern area where the Yarragadee Formation is absent and where the Cattamarra Coal Measures has been block faulted upwards into juxtaposition with the Yarragadee Formation. This unit is conformably overlain by the Yarragadee Formation beneath most of the Perth Region, except in the southern area, where it is unconformably overlain by the Gage Formation, South Perth Shale, Leederville Formation (Mariginiup Member) or the superficial formations (Fig. 75). The Cattamarra Coal Measures lies at depths ranging from about 10 to 400 m and is of Pliensbachian to Aalenian age (Cockbain, 1990).

4 Hydrogeology

The geological formations of the Perth Region have been grouped into seven distinct aquifers, each being assigned the name of the major geological unit contributing to the existence of the aquifer. Aquifers of these groups are locally hydraulically connected and, elsewhere, they are separated by major confining beds or by the distribution of the geological formations and faulting. The relationships of the geology to the aquifers and confining beds are given in Table 2, which also shows the stratigraphic sequence.

Groundwater in the Quaternary superficial formations is contained in a regional unconfined aquifer system (Allen, 1976, 1981a; Cargeeg et al., 1987; Davidson, 1995) and is locally in hydraulic connection with the underlying Tertiary and Mesozoic formations that form the semi-confined and confined aquifer systems. The unconfined superficial aquifer occurs mainly onshore while the confined aquifers extend several kilometres offshore to the west, where they are influenced by faulting (Fig. 76). In the Perth Region, the confined aquifers have been investigated for groundwater production to a depth of about 1100 m.

4.1 Superficial aquifer

The superficial aquifer is arbitrarily bounded to the north by the northern boundary of the Gingin Groundwater Area, south by the Murray River, east by the Gingin Scarp and Darling Fault, and to the west by the Indian Ocean shoreline. It is a major unconfined aquifer comprising the Quaternary-Tertiary sediments of the Swan Coastal Plain referred to by Allen (1976) as the superficial formations (Fig. 6).

From east to west, the sediments of the superficial aquifer generally vary from being predominantly clayey (Guildford Clay) adjacent to the Darling Fault and Gingin Scarp, to a sandy succession (Bassendean Sand and Gnangara Sand) in the central coastal plain area, and to sand and limestone (Safety Bay Sand, Becher Sand, and Tamala Limestone) within the coastal belt. Over most of the area the aquifer directly overlies sediments of Cretaceous age. In the Swan River estuary area, the superficial aquifer rests on the early Tertiary Kings Park Formation, and in the Rockingham area it rests on the Rockingham Sand (Fig. 13). The aquifer has a maximum saturated thickness of about 70 m, but over most of the northern region it has an average thickness of about 50 m. In the southern region the average thickness is about 20 m (Fig. 77).

The upper surface of the saturated superficial aquifer is the watertable (Fig. 78), which varies in depth (Fig. 79) depending mainly on topography (Fig. 5), but also on the hydraulic conductivity (permeability) of the sediments and location within the groundwater flow system. Over much of the central area of the Bassendean Dunes and beneath the low-lying areas of the Spearwood Dunes, the watertable intersects the surface, as indicated by the many lakes and swamps and the large areas of groundwater inundation during winter. As a consequence of the varying hydraulic conductivities, the watertable fluctuates seasonally by about 3 m in areas of clay adjacent to the Darling Fault and Gingin Scarp, by about 1.5 m in the central sandy area, and by less than 0.5 m in limestone along the coast. The watertable is highest during September-October and lowest during April-May.

The watertable contour configuration (Fig. 78) is dominated by the presence of two major groundwater mounds: the Gnangara Mound and Jandakot Mound, in the central coastal plain area. The presence of these mounds is determined mainly by the regional topography and partly by the drainage pattern, with drainage developed parallel to, and at the base of, the Gingin and Darling Scarps, and partly by the hydraulic characteristics of the sediments. The superficial aquifer of the Perth Region has been divided into discrete hydrogeological areas on the basis of topography, geology, and the discharge boundaries formed by the rivers and the ocean.

4.1.1 Hydraulic properties

The hydraulic properties of the superficial aquifer vary significantly depending on geology. The Guildford Clay consists of clayey sediments and has a low hydraulic conductivity of less than 0.1 metres per day (m/day), although some basal sandy lenses have a horizontal hydraulic conductivity of up to 10 m/day. The average horizontal hydraulic conductivity is about 15 m/day for the Safety Bay Sand, 8 m/day for the Becher Sand, and 8 to 10 m/day for the Yoganup and Ascot Formation (Table 2).

The Bassendean and Gnangara Sands represent highly permeable sandy materials. Over the entire area of the Bassendean Sand, the horizontal hydraulic conductivities for the Bassendean Sand range between 10 and 50 m/day, with an average of 15 m/day. In the Jandakot area, where the 'coffee rock' is generally thicker than elsewhere, the limonite cement may reduce the horizontal hydraulic conductivity to less than 10 m/day. The horizontal hydraulic conductivities for the Gnangara Sand range between 10 and 50 m/day but are generally about 20 m/day.

The hydraulic conductivity of the Tamala Limestone is highly variable and poorly understood. It is estimated that in areas where the limestone contains numerous solution channels and cavities that are often associated with the current or previous watertable, the horizontal hydraulic conductivities range between 100 and 1000 m/day. However, on a regional scale, the average horizontal hydraulic conductivity is influenced mostly by the low conductivity beds or sandy facies and may be about 50 m/day. In some local areas the limestone is tightly cemented with siliceous materials and is almost impermeable. In these areas the horizontal hydraulic conductivities may be less than one metre per day.

4.1.2 Groundwater flow

Groundwater flow in the superficial aquifer is influenced by gravity, down hydraulic gradient, and away from the crests of the groundwater mounds and foothills of the Dandaragan and Darling Plateaus. The direction of flow is indicated on the watertable contour map (Fig. 78) by the arrows on the flowlines, which terminate at the discharge boundaries formed by the major drainages and the ocean, and locally some of the wetlands. Beneath most of the Perth Region, the groundwater flowlines are divergent, indicating a net recharge. However, near wetlands and areas of high groundwater abstraction they are commonly locally convergent, indicating discharge.

The groundwater regime has been affected by human activity such as clearing of bushland for agriculture, urban development, drainage, and groundwater abstraction. Clearing the bushland for pasture and livestock grazing has facilitated rainfall recharge and caused rising groundwater levels. Large areas adjacent to, and west of, Ellen Brook (north of Perth), and many areas to the south of Perth, become inundated during winter and require drainage. Urban development has similarly induced additional rainfall recharge and some of the naturally occurring seasonal lakes are now permanently inundated. In other areas, the watertable has been lowered by groundwater abstraction and some of the naturally occurring lakes and swamps have become permanently dry or contain water for shorter periods of the year.

The hydraulic gradients, depicted by the horizontal separation of the watertable contours, vary across the coastal plain mainly because of the variations in aquifer thickness and hydraulic conductivities, but also because of areal variations in rainfall recharge and the location of groundwater discharge boundaries. In the eastern area of clayey sediments, where the hydraulic conductivities are generally less than 10 m/day the hydraulic gradients are relatively steep in comparison with those in the central sandy area of the coastal plain. In the eastern area, the hydraulic gradients are also generally steeper towards the discharge boundaries formed by the drainages that subparallel the Gingin and Darling Scarps. In the central sandy area, where the hydraulic conductivities vary with lithology and range from 10 m/day to more than 50 m/day, but average about 15 m/day, the hydraulic gradients are relatively uniform. In the western area, at about the contact between the Bassendean Sand and the Tamala Limestone (Fig. 6) and roughly coinciding with the north–south trending linear chain of lakes, the hydraulic gradients are relatively steep due to the high hydraulic conductivities (50–1000 m/day) of the Tamala Limestone to the west, which facilitates groundwater flow in this direction, resulting in a draining effect of the groundwater from the east and the steeper gradients. The hydraulic gradients within the Tamala Limestone are very low owing to the high hydraulic conductivity of the limestone.

The rate of groundwater flow through the superficial aquifer ranges from less than 50 m/year to more than 1000 m/year depending on geological location; it is greatest in the Tamala Limestone and least in the Guildford Clay.

4.1.3 Groundwater recharge

Groundwater recharge to the superficial aquifer is highly variable. The groundwater mounds, the foothills, and the rest of the study area represent three typical recharge types. Rainfall over each of these areas readily percolates to the watertable but recharge rates may vary considerably, depending on rainfall, landuse, and geology. In this report, a preliminary estimate of rainfall recharge has been made on a regional scale, using the methodology of Davidson (1995) that takes into account geology, topography and depth to watertable. The recharge areas and estimated recharge rates are shown in Figures 80 and 81.

The groundwater mounds (South Gnangara Mound, Jandakot Mound, Stakehill Mound and Safety Bay Mound) are recharged directly by rainfall infiltration and, apart from at the discharge boundaries and a few drains, are characterised by the absence of surface flow. The groundwater mounds have developed because the rate of vertical rainfall infiltration is greater than the rate of horizontal groundwater flow through the aquifer, and a state of equilibrium is reached where the hydraulic gradient is sufficiently steep to enable all of the recharge water to be transmitted as groundwater flow. At this stage, the watertable will be at its maximum elevation. During periods of little or no recharge, the rate of horizontal groundwater flow exceeds that of the vertical infiltration and the mounds begin to subside as the watertable drops and the hydraulic gradients flatten. This cycle is repeated seasonally and, depending on the amount and intensity of the rainfall and evapotranspiration, results in the seasonal fluctuations in watertable levels.

The groundwater mounds appear in the sandy sediments that have infiltration capacity high enough to readily drain the rainwater from the land surface to the watertable. In these areas, the recharge rate depends on landuse, which determines the amount of rainwater reaching the land surface, and evapotranspiration. The net recharge to the superficial aquifer is between 10 and 40 per cent of the annual rainfall, with an average of about 20 per cent.

Along the foothills of the Gingin and Darling Scarps, where the Guildford Clay is commonly present, there may be some recharge from minor ephemeral streams debouching from the Dandaragan and Darling Plateaus and dissipating on the coastal plain. The area is characterised by the shallow watertable and flat wetlands, and has low and continuous vertical recharge to the watertable. The watertable may be seasonally ‘perched’ above the Guilford Clay. The recharge rate depends on geology and drainage conditions, and ranges from 5 to 20 per cent of the annual rainfall, with an average of 10 per cent.

Direct rainfall recharge also occurs over the northern region, including North Gnangara Mound, Gingin, Swan Helena, and the southern region including the Cloverdale, Armadale, Byford, and Serpentine areas. In these areas, the recharge rate depends on geology and landuse. Soil infiltration capacity is low and causes a general reduction in recharge rate, due to significant clay contents of the sediments. The recharge rate ranges from 5 to 60 per cent of the annual rainfall, with an average of 15 per cent.

Some recharge to the superficial aquifer also occurs by upward leakage and discharge of groundwater from the underlying aquifers (Fig. 80). This appears in areas where there are increasing hydraulic heads with depth and where confining beds are absent between the underlying aquifers and the superficial aquifer. Within the urban areas, some recharge to the superficial aquifer also occurs as a result of garden and parkland irrigation of imported (scheme) water or water obtained from the deeper aquifers.

4.1.4 Groundwater discharge

Groundwater moves very slowly through the superficial aquifer and it is eventually discharged at the hydraulic boundaries formed by the rivers, ocean, and some of the lakes. During movement, it is recharged by rainfall infiltration and discharge is by evaporation from wetlands, transpiration from vegetation where roots are able to reach the capillary fringe associated with the watertable, leakage into underlying aquifers where there are downward hydraulic gradients and confining beds are absent, and by abstraction of groundwater from boreholes (Fig. 80). The superficial aquifer transmissivity, which provides a quantitative measure of aquifer yield or discharge capacity, is highly variable over the study area (Fig. 82), depending on the saturated thickness and hydraulic conductivity of the superficial aquifer.

Groundwater in the superficial aquifer also discharges through natural and constructed drainages into wetlands, and at springs. Springs occur mainly adjacent to the major drainages, where the watertable has intersected the levee banks. This mostly results in a wetted area at the land surface, but at some localities springs may be present. Similarly, along the eroded coastline, groundwater discharges through a seepage face and forms small springs along rocky parts of the coast (Allen, 1981b). Some discharge takes place offshore from springs connected to solution channels within the Tamala Limestone.

At the end of its flow path, groundwater discharges into the ocean, Peel Inlet, and the Swan River estuary over a saltwater wedge that forms the interface between land- and ocean-derived groundwater. The elevation of the watertable near the coast is controlled by the ocean level and the prevailing climatic conditions over the recharge area to the east.

4.1.5 Groundwater storage

The volume of groundwater in storage in the superficial aquifer, represented by the amount of water in pore spaces in the sediments available to bores if the sediments are dewatered, can be calculated using the contour map of the aquifer saturated thickness (Fig. 77). Estimated specific yields are 0.30 for the coastal belt of Tamala Limestone, 0.20 for the central area of Bassendean Sand and Gnangara Sand, and 0.05 for the area of the Guildford Clay. The total available groundwater held in storage within the superficial aquifer is about $60\,000 \times 10^6$ m^3.

4.2 Rockingham aquifer

The Rockingham aquifer exists only in the southern Perth Region. It is a minor, but locally important, semi-unconfined aquifer comprising the late Tertiary Rockingham Sand. The aquifer has a known onshore thickness of 80 m, and consists of slightly silty and felspathic, medium to coarse sand, with an average hydraulic conductivity of about 20 m/day. The age of the groundwater in the Rockingham aquifer is not known but it is probably similar to that at the base of the superficial aquifer (~2000 years).

The Rockingham aquifer is used extensively for irrigation of parklands and sporting areas. The basal 70 m contains ocean water, and the upper 40 m contains fresh (<1000 mg/L TDS) groundwater. Discontinuous clay lenses at the base of the superficial formations locally confine the Rockingham aquifer from the overlying superficial aquifer. Regionally, however, the two aquifer systems are hydraulically connected and commonly have similar horizontal hydraulic conductivities, resulting in the Rockingham aquifer being semi-unconfined. The Rockingham aquifer is also hydraulically connected to the Leederville aquifer through unconformable contact.

4.2.1 Groundwater recharge

Groundwater in the Rockingham aquifer is in hydraulic continuity with groundwater in the overlying superficial aquifer and is recharged by downward groundwater leakage. The amount of recharge varies from year to year depending mainly on climatic factors, of which rainfall is the most important. As the head difference between the watertable in the superficial aquifer and the potentiometric level of the Rockingham aquifer changes, the recharge rate to the Rockingham aquifer will also change. Abstraction of groundwater from the Rockingham aquifer will increase the head difference and induce additional recharge. Groundwater also enters the Rockingham aquifer, along its eastern margin, as groundwater discharge from the Leederville aquifer. This occurs above a saltwater interface.

4.2.2 Groundwater flow and discharge

The groundwater flow system of the Rockingham aquifer has not been fully investigated and only estimates of throughflow and storage can be made. Groundwater flows westward in the Rockingham aquifer over a saltwater interface derived from the ocean. It then discharges along the coast and possibly offshore via the superficial aquifer. The depth to the saltwater interface in the Rockingham aquifer has not been delineated by drilling except at AM54, AM57 and AM58 where it is about 70, 65, and 75 m below ground level, respectively.

4.2.3 Groundwater storage

Groundwater of salinity less than 1000 mg/L TDS in the top 40 m of the Rockingham aquifer overlies saline water. However, in areas close to the coast, groundwater is saline in the aquifer as indicated by drilling at AM67. The volume of fresh groundwater (<1000 mg/L) above the saltwater interface can be estimated using an average specific yield of 0.2, and is about 2200 × 10^6 m^3. The volume will vary depending on the position of the saltwater interface, which will be affected in turn by groundwater abstraction from the aquifer.

4.3 Kings Park aquifers

The Kings Park aquifers consist of two aquifers within the Kings Park Formation, but they are of only local and limited importance. They are the early Tertiary Mullaloo Sandstone Member and Como Sandstone Member, which form minor semi-confined to confined aquifers. The Mullaloo Sandstone has a known onshore maximum thickness of 170 m, and consists of fine- to very coarse-grained and clayey sand with a horizontal hydraulic conductivity of about 10 m/day. The Como Sandstone has a known onshore maximum thickness of 57 m and consists of predominantly medium-grained and slightly clayey sand with an average horizontal hydraulic conductivity of about 15 m/day.

The Kings Park aquifers have been identified within the boundary of the Kings Park Formation but the extent of each has not been delineated. Other similarly occurring sandy beds may exist within the Kings Park Formation and provide local sources of groundwater. The age of the groundwater in the Kings Park aquifers is not known.

4.3.1 Groundwater recharge

Recharge to the Mullaloo Sandstone Member and the Como Sandstone Member occurs where they extend to the boundary of the Kings Park Formation and where they are in hydraulic contact with the superficial, Mirrabooka, Leederville, and Yarragadee aquifers. In these areas recharge is by lateral groundwater movement and discharge from these older aquifers.

As the recharge areas to the Kings Park aquifers have not been delineated, the quantity of recharge cannot be calculated with any certainty. It is suggested that the upper aquifer (Mullaloo Sandstone Member) is recharged by downward leakage from the superficial aquifer and by lateral flow and groundwater discharge from the Mirrabooka aquifer. The lower aquifer (Como Sandstone Member) is probably recharged by groundwater discharge from the Leederville and Yarragadee aquifers.

4.3.2 Groundwater flow, discharge and storage

More detailed drilling and testing is required to define flow directions and permit estimates of quantity of flow and groundwater storage in the Kings Park aquifers.

Groundwater within the Kings Park aquifers eventually discharges westward over a saltwater interface and into the ocean. Groundwater in the Mullaloo Sandstone Member probably discharges into the superficial aquifer offshore but near the coast, while that from the Como Sandstone Member probably discharges some distance offshore.

4.4 Mirrabooka aquifer

The Mirrabooka aquifer comprises the Poison Hill and the Molecap Greensands, and the Mirrabooka Member. The aquifer is arbitrarily bounded to the north by the northern boundary of the Gingin Groundwater Area and elsewhere by the collective boundary of the Poison Hill Greensand, Gingin Chalk, Molecap Greensand, and Mirrabooka Member of the Osborne Formation, the geological units that constitute the aquifer. Contours on the upper and lower surfaces of the Mirrabooka aquifer are shown in Figures 83 and 84, respectively.

The Poison Hill Greensand has a known maximum thickness of 60 m and is largely unsaturated beneath the Dandaragan Plateau. It consists of fine to very coarse sand, or silty and clayey sand, and has an average horizontal hydraulic conductivity of about 10 m/day.

The Molecap Greensand has a known maximum thickness of 60 m, and consists of fine to medium, glauconitic, silty, or clayey sandstone. It has an average horizontal hydraulic conductivity of about 4 m/day. However, in some areas where this unit is less silty, it may have hydraulic conductivities of about 8 m/day.

The Mirrabooka Member has a known maximum thickness of 140 m (Fig. 85), and consists of fine to very coarse sandstone with thin interbeds of siltstone and shale. It has an average horizontal hydraulic conductivity of about 4 m/day.

The Mirrabooka aquifer is a locally important semi-confined to confined aquifer. The age of the groundwater in the Mirrabooka aquifer is not known, but is probably between 2000 and 10 000 years.

Beneath the Dandaragan Plateau, the Mirrabooka aquifer is mostly above the watertable and is unsaturated. Where it does contain groundwater, the aquifer is generally of low permeability and is recharged by rain infiltration. There are insufficient data to calculate the percentage of rainfall recharge to the Mirrabooka aquifer over the Dandaragan Plateau and only rough estimates can be made.

4.4.1 Groundwater recharge

The Mirrabooka aquifer is a semi-confined and locally confined aquifer that is present only in the northern Perth area, where it is confined below by shales of the Osborne Formation (Kardinya Shale Member) and locally by interbedded shale lenses within it. Beneath the coastal plain the groundwater in the Mirrabooka aquifer is in hydraulic continuity with the groundwater in the overlying superficial aquifer, and a component of downward groundwater flow in the superficial aquifer recharges the Mirrabooka aquifer. However, abstraction of groundwater from the Mirrabooka aquifer will significantly increase the head difference between the watertable and the potentiometric surface of the Mirrabooka aquifer, thereby inducing additional recharge.

The amount of recharge will vary slightly from year to year depending on climatic factors of which rainfall is the most important. As the head difference between the watertable in the superficial aquifer and the potentiometric level of the Mirrabooka aquifer changes, the recharge rate to the Mirrabooka aquifer will also change.

4.4.2 Groundwater flow and discharge

The direction of groundwater flow in the Mirrabooka aquifer is imprecisely known but it is believed that flow is southward. In the Swan Valley area the resultant groundwater flow in the Mirrabooka aquifer is south-eastward, and across the remainder of the metropolitan area it is assumed to be subparallel to the groundwater flow direction in the superficial aquifer (Fig. 79). Across the metropolitan area, the configuration of the potentiometric surface of the Mirrabooka aquifer is poorly defined and the potentiometric contours shown in Figure 86 are based on sparse data from the Mirrabooka aquifer, and widespread hydraulic head data from the base of the superficial aquifer.

Towards the end of the groundwater flow path, much of the groundwater throughflow in the Mirrabooka aquifer eventually discharges by upward leakage into the superficial aquifer (Fig. 86). The remainder flows laterally to discharge into the Mullaloo Sandstone Member or other unidentified sandy beds within the Kings Park Formation. In low-lying areas, where upward hydraulic heads occur, bores screened against the Mirrabooka aquifer may discharge naturally as artesian flows.

The Kardinya Shale Member of the Osborne Formation, between the Mirrabooka aquifer and the Henley Sandstone Member, inhibits downward groundwater leakage into the Leederville aquifer. There may be some leakage into the Leederville aquifer, but it is difficult to quantify and it may be insignificant.

4.4.3 Groundwater storage

The volume of groundwater in storage within the Mirrabooka aquifer has been estimated by applying an assumed specific yield of 0.2 to the accumulated sand bed saturated thickness of the aquifer (Fig. 85). Because the Mirrabooka aquifer is semi-confined, the volume of groundwater held in elastic storage can be estimated using a storage coefficient of 1×10^{-3}. Elastic storage is defined as being the amount of water per unit volume of a saturated formation that is stored or expelled from storage owing to compressibility of the formation per unit change in head. The total volume of groundwater in storage within the Mirrabooka aquifer is about $12\,100 \times 10^6$ m^3.

4.5 Leederville aquifer

The Leederville aquifer comprises the Leederville Formation (Pinjar Member, Wanneroo Member and Mariginiup Member) and Henley Sandstone Member of the Osborne Formation. Groundwater in the Leederville aquifer ranges in age from about 1900 years to more than 36 800 years, but is generally less than 36 000 years (Thorpe and Davidson, 1991).

The Leederville aquifer is a major confined aquifer underlying the Perth Region. It overlaps the Darling Fault south of the Dandaragan Plateau and ranges both to the north and to the south of the study area. The Leederville aquifer extends beneath the entire coastal plain except in the north near the Swan Estuary, where the Leederville Formation has been eroded out prior to deposition of the Kings Park Formation (Fig. 42), and in the south-east corner, where the superficial formations rest directly on the Cattamarra Coal Measures (Fig. 13). The Leederville aquifer is a multilayer groundwater flow system that is arbitrarily bounded to the north and to the south by the Gingin Groundwater Area and Murray River respectively, to the east by the Darling Fault, and to the west by the fault line delineating the boundary of the Perth Region. The aquifer is unconfined at the intake areas where it directly underlies the superficial aquifer, but over short distances it becomes confined by the discontinuous interbeds of siltstone and shale within it. Elsewhere, it is confined above by the Lancelin Formation and Kardinya Shale Member of the Osborne Formation (Fig. 87) and below by the South Perth Shale (Fig. 88).

4.5.1 Hydraulic properties

The Leederville aquifer has a maximum thickness of more than 600 m in the Yanchep Syncline (Figs 41, 44). In the northern part of the Swan Syncline and in the Wanneroo area it is about 550 and 400 m thick, respectively. Across the Pinjar Anticline it has a minimum thickness of about 50 m. South of Perth, the Leederville aquifer ranges in thickness from about 50 m in the south-east to some 300 m beneath the Jandakot area (Fig. 89).

The Leederville aquifer is a multilayered aquifer consisting of discontinuous interbedded sandstones, siltstones and shales in the general proportion of 50 per cent sandstone to 50 per cent siltstone plus shale. As a consequence, the average horizontal hydraulic conductivity will range between the harmonic mean and the arithmetic mean of the local hydraulic conductivities (de Marsily, 1986). Details of calculation are given by Davidson (1995) and illustrated in Figure 90.

From pumping tests (Smith, 1979), the horizontal hydraulic conductivity of the sandstone beds is about 10 m/day and that of the siltstone and shale beds assumed to be about 1×10^{-6} m/day. If the interbedded lenses are laterally discontinuous over short distances, the average hydraulic conductivity of the aquifer will approach 1×10^{-6} m/day with the harmonic mean being dominated by the local hydraulic conductivity of the siltstones and shales. If the interbedded sandstones, siltstones and shales are laterally extensive, then the average horizontal hydraulic conductivity will approach 5 m/day with the arithmetic mean being dominated by the hydraulic conductivity of the sandstone beds, which occupy approximately half the aquifer thickness. North of the Swan River the average hydraulic conductivity values range between 1 and 10 m/day (average k = 2 m/day) and south of the river they range between 0.1 and 1 m/day (average k = 0.5 m/day). These values indicate that the individual sandstone beds within the Leederville aquifer are reasonably extensive.

4.5.2 Groundwater flow

The potentiometric surface of the Leederville aquifer, based on hydraulic head measurements obtained from the artesian monitoring (AM) bores and other investigation bores perforated approximately in the middle of the aquifer, fluctuates seasonally by one to 15 m. Over most of the area the seasonal variation is less than 5 m, but in areas of high groundwater abstraction from the Leederville aquifer, variations commonly exceed 10 m. The configuration of the potentiometric surface for November 1997 is shown in Figure 91. In the northern area, the potentiometric surface slopes predominantly south-westward from beneath the Dandaragan Plateau. In the south, this aquifer slopes westward from the eastern margin of the coastal plain. In the central Perth area, the shape of the potentiometric surface has been affected by groundwater abstraction, as shown by the near closures of the five and 10 m potentiometric contours.

The direction of groundwater flow north of the Swan River is generally to the south-west, except beneath the Swan Valley where some flow is to the south-east; south of the Swan River groundwater flow is westward.

Artesian groundwater flows can be expected from bores drilled into the Leederville aquifer in low-lying areas along the valleys of the Swan, Canning, Southern, and Serpentine Rivers and in low-lying areas along the coastal strip.

4.5.3 Groundwater recharge

The Leederville aquifer subcrops beneath the superficial formations over about half of the coastal plain in the Perth Region where the Osborne Formation shale (Kardinya Shale) has been removed by erosion (Fig. 87). In these areas it is in direct contact and hydraulic connection with the superficial aquifer and, where there is a downward hydraulic gradient, recharge occurs (Fig. 91). In the northern area, recharge is mainly over the Pinjar Anticline. Beneath the area of the Dandaragan Plateau, the Leederville aquifer is overlain by the Greensand and Osborne Formation and recharge to the aquifer takes place only where deep valleys have been incised to expose the aquifer in the many creek beds, enabling infiltration of stream flow to occur. To the south of Perth, recharge to the Leederville aquifer mainly occurs along the eastern margin of the coastal plain. However, because of declining hydraulic heads within the aquifer, the area of downward heads is getting larger and the recharge area is gradually extending westward. Vertical leakage through shales may be insignificant.

Recharge to the Leederville aquifer also occurs by upward discharge from the Yarragadee aquifer in areas where the South Perth Shale confining bed between the aquifers is absent or thin and where there are increasing heads with depth and upward hydraulic gradients.

4.5.4 Groundwater discharge

Groundwater in the Leederville aquifer flows westward and eventually discharges offshore into the ocean via the superficial formations. Onshore, some groundwater in the Leederville aquifer discharges into the superficial aquifer where the Kardinya Shale Member is absent and where there are increasing heads with depth and upward hydraulic gradients (Fig. 91).

Beneath the Perth area where the Cretaceous sediments have been eroded prior to deposition of the Kings Park Formation, groundwater discharges, by lateral flow, into the sandstone beds of the Kings Park Formation (Mullaloo Sandstone and Como Sandstone Members). The quantity of groundwater discharging to the Kings Park Formation depends on the amount of groundwater abstraction from the Leederville aquifer adjacent to the discharge area. This is because the effects of abstraction will induce groundwater to flow towards the abstraction area and away from the discharge area.

Beneath the Rockingham area where the Leederville Formation has been eroded to a depth of about 100 m prior to deposition of the Rockingham Sand, approximately half of the groundwater throughflow discharges into the Rockingham aquifer over a saltwater interface. The remaining groundwater throughflow flows westward beneath the Rockingham Sand to eventually discharge offshore into the ocean.

In areas where the South Perth Shale is absent and there are decreasing heads with depth (downward hydraulic gradients), groundwater leaks downwards into the Yarragadee aquifer.

4.5.5 Groundwater storage

Groundwater in the Leederville aquifer is contained in the interbedded sandstones, siltstones and shales, but only that which is stored in the sandstone beds is considered readily available for abstraction. The average sandstone: siltstone + shale ratio, calculated from wireline gamma-ray logs of the artesian monitoring (AM) boreholes for the Leederville aquifer, is about 0.5. This ratio is highest where the Wanneroo Member is thickest and lowest where the Mariginiup Member is thickest. On average, the Henley Sandstone Member has a ratio of about 0.7, the Pinjar Member a ratio around 0.5, the Wanneroo Member a ratio of about 0.6 and the Mariginiup Member a ratio of about 0.3.

The volume of unconfined groundwater held in storage within the sandstone beds of the Leederville aquifer has been estimated from the isopach map of the Leederville aquifer (Fig. 89) and using an average sandstone: siltstone + shale ratio of 0.5 and an assumed specific yield of 0.2 for the sandstone beds. Since the Leederville aquifer is confined, the elastic storage of the sandstone beds can be estimated using an average storage coefficient of 1×10^{-4}. The total volume of groundwater in storage beneath the Perth Region is about $280\,000 \times 10^{6}$ m^3.

4.6 Parmelia Sand aquifer

The Parmelia aquifer comprises the Parmelia Sand Member west of the Muchea Fault. The aquifer is bounded arbitrarily to the north by the northern boundary of the Gingin Groundwater Area, to the south by the geological boundary of the Parmelia Sand Member, to the east and west by the eastern and western boundaries of the Parmelia Sand Member. The Parmelia Sand aquifer was previously included in the Yarragadee aquifer (Davidson, 1995).

The Parmelia aquifer occurs in the north-eastern area of the Swan Syncline, where it is a widespread but low-yielding confined aquifer, confined above by shales of the Carnac Member of the Parmelia Formation west of the Muchea Fault. Contours on the upper and lower surface of the Parmelia aquifer are shown in Figures 92 and 93, respectively.

The Parmelia aquifer has an estimated maximum thickness of 750 m (Fig. 94), and consists of sandstone with thin interbeds of siltstone and shale. The sandstone consists of predominantly medium sand in a weak kaolinitic or siliceous cement. The average horizontal hydraulic conductivity of the Parmelia Sand Member is less than two metres per day. The sandstone beds are lithologically similar to those of the upper part of the Yarragadee Formation.

4.6.1 Groundwater recharge

Groundwater recharge to the Parmelia aquifer is by downward leakage through the Leederville aquifer where the Carnac Member is absent or very thin. Since the Carnac Member is generally widespread and relatively thick, recharge to the Parmelia aquifer is small and limited to local areas.

4.6.2 Groundwater flow and discharge

Groundwater flows in a southerly direction within the Parmelia aquifer; however, the configuration of the potentiometric surface (Fig. 95) is not well defined and has been approximated.

Groundwater in the Parmelia aquifer discharges into the Yarragadee aquifer in areas where the Otorowiri Member is absent, very thin or slightly permeable. There are insufficient data to determine the discharge boundary of the aquifer. Some groundwater may discharge upwards into the Leederville aquifer where the Carnac Member is permeable or very thin.

4.6.3 Groundwater storage

Based on the isopach map of the Parmelia aquifer (Fig. 94) and estimates of storage coefficient and specific yield, the total groundwater in storage is about 28 000 × 10^6 m^3.

4.7 Yarragadee aquifer

The Yarragadee aquifer is a major confined aquifer underlying the Perth Region and extending to the north and south within the Perth Basin. It is a multilayered aquifer more than 2000 m thick. The aquifer consists of the Yarragadee Formation and Gage Formation over most of the study area, but in the south-eastern area, the Cattamarra Coal Measures (Fig. 75) is the major component of the aquifer. Only about the upper 500 m of the aquifer have been investigated by drilling. The groundwater in the Yarragadee aquifer ranges in age from about 600 years in the intake area to the south of Perth, to more than 37 700 years elsewhere and is generally older than 36 000 years (Thorpe and Davidson, 1991).

The Yarragadee aquifer considered in this study is arbitrarily bounded to the north and the south by the northern boundary of the Gingin Groundwater Area and Murray River respectively, to the east by the Darling Fault, and to the west by the western boundary of the Perth Region. This aquifer comprises the Cretaceous Gage Formation and the Jurassic Yarragadee Formation and Cattamarra Coal Measures. The Parmelia Sand aquifer was previously included in the Yarragadee aquifer.

In some areas beneath the Swan Coastal Plain, the Yarragadee aquifer is confined by the South Perth Shale. To the east of the Gingin Scarp, and beneath the Dandaragan Plateau, it is confined by the Otorowiri Member of the Parmelia Formation. In the central northern part of the coastal plain where there are no confining beds, the Yarragadee aquifer is in direct hydraulic contact with the Leederville aquifer.

4.7.1 Hydraulic properties

The Yarragadee aquifer is a multilayer aquifer consisting of discontinuous interbedded sandstones, siltstones and shales in the general proportion of 50 per cent sandstone to 50 per cent siltstone plus shale. As a consequence of the lensing nature of the interbedded sandstones, siltstones and shales, the average horizontal hydraulic conductivities range between 1 × 10^{-6} and 10 m/day. The average rate of groundwater flow through the Yarragadee aquifer is about 0.9 m/year, confirming the very slow rate of flow indicated by the ^{14}C dating of the groundwater (Davidson, 1995; Thorpe and Davidson, 1991).

The hydraulic properties of the Yarragadee aquifer vary with locations. Within the Yanchep and Swan Synclines, the formation is non-marine, probably fluvial, and the individual sandstone beds are up to 30 m thick. They consist of pale grey, medium- to very coarse-grained, poorly sorted, slightly felspathic and weakly cemented sand with horizontal hydraulic conductivities ranging up to 10 m/day. The siltstones and shales are of similar thickness to the sandstone beds and are commonly pyritic and micaceous (Allen, 1981a). Within the area of the Pinjar Anticline and particularly beneath the Wanneroo area, the Yarragadee Formation was probably laid down in a shallow-marine or paralic environment. Here the sandstones are of thickness similar to those elsewhere but they are generally finer grained and better sorted. Thinly interbedded sandstones, siltstones and shales also occur throughout the entire thickness of the Yarragadee Formation. The discontinuous nature of the sandstone beds has lowered the average horizontal hydraulic conductivity to about one metre per day.

4.7.2 Groundwater flow

Contours on the upper and lower surfaces of the Yarragadee aquifer are shown in Figures 96 and 97 respectively. The thickness of the aquifer is given in Figure 98. In two small areas to the south-east, where the Cattamarra Coal Measures is directly overlain by the superficial formations (Fig. 75), groundwater in the Yarragadee aquifer is in hydraulic continuity with that in the superficial aquifer. Groundwater within the Yarragadee aquifer is also in hydraulic continuity with groundwater in the Leederville aquifer where the South Perth Shale is absent on the crest of the Pinjar Anticline, north of Perth, and adjacent to the Darling Fault, south of Perth. Downward hydraulic heads occur in the recharge areas (Fig. 99) and artesian flows can be expected from bores drilled in topographically low areas away from the intake areas.

Regional groundwater flow within the Yarragadee aquifer is south-westward (Fig. 99) based on the configuration of the potentiometric surface for September to October 1997. The potentiometric surface is generally 10 to 20 m higher north of Perth than it is south of Perth, reflecting the effect of the regional topography and elevations of the watertable within the respective recharge areas.

Over wide areas, particularly in the southern area, the gradient on the potentiometric surface is relatively flat, indicating that the rate of groundwater movement is very slow. The potentiometric surface varies approximately in phase with rainfall, and seasonally by less than one metre. However, in areas of groundwater abstraction from the Yarragadee aquifer, the seasonal variations in potentiometric levels may be up to seven metres. The configuration of the potentiometric surface near Perth is uncertain because of lack of data where the Kings Park Formation occupies a channel eroded into the Yarragadee Formation.

It is likely that most of the groundwater flow occurs in the top part of the aquifer, at least in the top 500 m, and that beneath this depth, the increasing groundwater salinity indicates a lack of flushing, implying limited groundwater flow (Davidson, 1995).

4.7.3 Groundwater recharge

Groundwater recharge to the Yarragadee aquifer is by downward leakage of groundwater from the Leederville aquifer where the South Perth Shale is absent and a downward hydraulic head occurs (Fig. 99), and also from the superficial aquifer in the south-east where the superficial formations rest directly on the Cattamarra Coal Measures (Fig. 13). Groundwater recharge also occurs by downward leakage of groundwater from the superficial aquifer in the northern Gnangara Groundwater Mound, where the Yarragadee aquifer is directly overlain by the superficial aquifer. Some recharge may also pass though the superficial aquifer from local streams discharging runoff from the Darling Plateau and dissipating over the south-eastern margin of the coastal plain (Allen, 1979), but this has not been verified.

4.7.4 Groundwater discharge

Groundwater discharges from the Yarragadee aquifer into the Leederville aquifer in areas where there are upward hydraulic head differentials and where the confining South Perth Shale is absent (Fig. 99). Most of the groundwater throughflow in the Yarragadee aquifer discharges offshore, possibly over a series of saltwater wedges, into the overlying strata.

Near Perth, some of the groundwater in the Yarragadee aquifer discharges into sandy beds of the Como Sandstone Member within the Kings Park Formation, and possibly into the Leederville aquifer (Allen, 1981a) along the contact margin of the Kings Park Formation (Fig. 16).

4.7.5 Groundwater storage

There is a very large volume of fresh to saline groundwater in storage within the Yarragadee aquifer beneath the Perth Region. However, the groundwater is fresh only in the intake areas where the groundwater salinity is less than 1000 mg/L TDS to depths ranging to about 500 m below the top of the aquifer. In the Wanneroo area, production bore W257 drilled 293 m into the Yarragadee aquifer and, at a depth of 1108 m (528 m below the base of the Leederville Formation), it had not fully penetrated the fresh groundwater zone. Away from the intake areas, the groundwater becomes increasingly brackish.

Based on a sandstone: siltstone and shale ratio of 0.5; an assumed specific yield of 0.2 for the sandstone beds, and an average thickness of 1000 m for the aquifer, there is about 950 000 × 10^6 m^3 of groundwater in storage.

5 Groundwater modelling — concept and model design

5.1 Introduction

The development of the hydrogeological conceptual model for the Perth Region is based on the description of geology and hydrogeology in the above sections. The conceptual model represents the understanding and visualisation of the groundwater flow system in the Swan Coastal Plain and the Dandaragan Plateau. The hydrogeological conditions and hydrological processes in the multilayered and hydraulic connected aquifers were generalised and simplified in the conceptual model.

Modflow (McDonald and Harbaugh, 1988) was selected for the model development. The concept and design of the model are described below, using the context and terminology of Modflow. The development of a numerical model based on the conceptual model is discussed in other volumes of the PRAMS report series (Silberstein, et al., 2004; CyMod Systems, 2004).

The aquifers and confining beds are represented by layers in the model. The geological surfaces used to build the PRAMS model are shown in the figures in this report, except that surfaces in the onshore area south of Gingin Brook are those of Davidson (1995). Minor changes to the surfaces of Davidson (1995) are therefore not incorporated. Estimated hydraulic properties are assigned to the layers as initial values and have been altered through the model calibration. Spatial distributions of the hydraulic properties in each layer are represented by zones within which the properties are considered to be constant.

Major hydraulic processes are generalised and simplified so that they can be represented by modules in Modflow. The generalisation and simplification are essential processes through which the real or hypothetical hydrogeological conditions and processes are visualised to emphasise the purpose of model development, and the selection of modelling software (Anderson and Woessner, 1992). Initial and boundary conditions are assigned to the model to establish a preliminary simulation.

A simplified representation of aquifer relationship in the Swan Coastal Plain is shown in Figure 100. The study area has a multilayered aquifer system that is bounded by the Darling Fault to the east and the coast (for the superficial aquifer) or the nearest offshore geological fault (for the confined aquifers) to the west. The most important geological structure is the Pinjar Anticline, where some confining beds have been eroded and the confined aquifers subcrop beneath the superficial aquifer.

The model design for the aquifer system is illustrated in Figure 101. The model is composed of 12 layers including seven aquifers and five confining beds. The model layers and hydrogeological characterisations of the layers are described in the order of increasing depth.

It is assumed that all model layers extend over the entire model domain, as required by the Modflow software program. The thickness of the aquifer layer is zero in areas where the aquifer is absent, and the model layers in these areas are called 'dummy layers' in the modelling approach. Detailed discussion about this approach can be found in the Modflow manual (McDonald and Harbaugh, 1988).

5.2 The model layout

5.2.1 Layers 1 and 2 — Superficial aquifer

The superficial aquifer is represented by two model layers to account for the vertical hydraulic gradient and the need for refinement of wetland-groundwater interaction near the watertable. Layer 1 represents the watertable and the uppermost five metre saturated part of the superficial aquifer. The upper surface of Layer 1 is defined by the watertable elevation on the Swan Coastal Plain, and by the potentiometric surfaces of the Mirrabooka or Leederville aquifers on the Dandaragan Plateau where the superficial aquifer is absent (Fig. 102). The thickness of Layer 1 is five metres over the Swan Coastal Plain, and zero on the Dandaragan Plateau where the superficial aquifer is not present. About 330 watertable monitoring bores were used for watertable calibration or validation.

Layer 2 represents the main part of the superficial aquifer, and has a saturated thickness ranging from 5 to 50 m across the Swan Coastal Plain. The upper surface of Layer 2 is a hypothetical surface five metres below the watertable on the Swan Coastal Plain (Fig. 103). About 300 monitoring bores were used for superficial aquifer calibration or validation. It was assumed that Layer 2 has the same upper surface as Layer 1 on the Dandaragan Plateau where neither layer was present and where both layers have zero thickness.

Figure 13 shows that the base of the superficial aquifer (the base of Layer 2) is in direct contact with the Rockingham aquifer in the south-west, and the Mirrabooka aquifer in the north-east of the study area. The base of Layer 2 is also in direct contact with the Leederville aquifer in the central area of the Gnangara Groundwater Mound, and also the Yarragadee aquifer at the far north-western part of the model. The base of Layer 2 is also in direct contact with confining beds represented by the Kings Park Formation, the Lancelin Formation, and the Kardinya Shale in the central Perth metropolitan area. Direct contact between the aquifer layers provides better hydraulic connections and recharge conditions.

5.2.2 Layer 3 — Rockingham and Mirrabooka aquifers

Layer 3 comprises the Rockingham aquifer and the Mirrabooka aquifer, which are geographically separated. The Rockingham aquifer, which is located in the south-western part of the model (Fig. 14), has a thickness of up to 80 m in the Rockingham area, and is in direct contact with the overlying superficial aquifer and the underlying Wanneroo Member of the Leederville Formation.

The Mirrabooka aquifer occurs in the northern Perth area, where its thickness is generally less than 100 m, except in the Mirrabooka area where it has a known thickness up to 140 m. The aquifer is in contact with the overlying superficial aquifer and is underlain by the Kardinya Shale confining bed.

The upper surface of Layer 3 is defined by the upper surface elevation of the Rockingham Sand and the Mirrabooka aquifer (Fig. 84) on the Swan Coastal Plain, and by the potentiometric surfaces of the Mirrabooka or Leederville aquifers on the Dandaragan Plateau. Figure 104 shows a schematic section near the Gingin Scarp where the upper surface of Layer 3 is made up from the potentiometric surface of the Mirrabooka and Leederville aquifers at the eastern section, and the base of the superficial aquifer at the western section. Figure 105 shows the contour map of the surface of Layer 3.

5.2.3 Layer 4 — Kings Park Formation, Lancelin Formation, and Kardinya Shale

Layer 4 comprises the Kings Park Formation, the Lancelin Formation, and the Kardinya Shale. It is a confining bed that separates Layers 2 and 3 from the underlying Leederville aquifer. The Kings Park Formation is located in the northern Perth metropolitan area from Carine to the Swan River. It becomes more extensive offshore (Fig. 16). The Kings Park Formation occupies a deeply eroded valley incised through the Cretaceous into the Jurassic sediments to a total thickness of up to 600 m. To avoid model stability problems that may occur if the Kings Park Formation is included in just one layer, the Kings Park Formation has been vertically divided into sections. Each section has been integrated into the respective layers located at the same depth. Figure 106 illustrates the sections of the Kings Park Formation that have been integrated into model layers.

The Lancelin Formation is located around the Lancelin area (Fig. 19). The Kardinya Shale Member flanks both sides of the Pinjar Anticline, and is in the Swan Valley and part of the Perth metropolitan area (Fig. 37).

The upper surface of Layer 4 is defined by the upper surface elevation of the Kardinya Shale Member, and the Lancelin Formation. The upper surface of Layer 4 is –100 m AHD over the area where the Kings Park Formation exists (Fig. 107). In areas where the Kardinya Shale or Lancelin Formations are absent, the upper surface of Layer 4 is defined by the upper surface of Layer 3, and the thickness of Layer 4 in these areas is zero.

5.2.4 Layers 5, 6 and 7 — Leederville aquifer

The Leederville aquifer is a regional confined aquifer and is represented by Layers 5, 6, and 7 in the model. Layer 5 is the upper layer of the Leederville aquifer and comprises the Henley Sandstone Member of the Osborne Formation and the Pinjar Member of the Leederville Formation.

The Henley Sandstone Member is located mainly beneath the Swan Valley and the northern Perth metropolitan area, where it has a thickness of about 80 m (Fig. 41). The Pinjar Member occurs in most onshore and offshore Perth areas (Fig. 47), with a thickness ranging from 50 m to over 100 m. The Pinjar Member has been eroded in the central Perth area and it is also absent near the northern and southern boundaries of the model.

Layer 5 has direct contact with the overlying superficial aquifer beneath the Pinjar Anticline (Fig. 45), and the Kardinya Shale Member along the Swan Valley and Perth metropolitan area. The layer is in direct contact with the underlying Wanneroo Member (Layer 6) in most of the Perth area, and with the Yarragadee Formation (Layer 11) at the northern boundary of the model. The upper surface of Layer 5 (Fig. 108) is defined by the surface elevation of the Leederville aquifer (Fig. 87). In areas where the upper Leederville aquifer is absent, it is defined by the base of the superficial aquifer on the Swan Coastal Plain (Fig. 13), and by the potentiometric surfaces of the Mirrabooka or Leederville aquifers on the Dandaragan Plateau where the superficial aquifer is absent.

Layer 6 is the middle layer and the most extensive part of the Leederville aquifer, and consists of the Wanneroo Member of the Leederville Formation. It occurs throughout most of the Perth area and has a thickness of up to 350 m in the northern Perth area, and around 100 m in the southern Perth area (Fig. 50). Layer 6 is in contact with the overlying Pinjar Member (Layer 5) over most of the model area, and with the superficial aquifer (Layer 2) in the central Perth area and at the southern boundary of the model. It is in contact with the underlying Mariginiup Member (Layer 7) over most of the model area, and with the Yarragadee and Parmelia Formations on top of the Pinjar Anticline. Layer 6 is also in direct contact with the Yarragadee Formation in the area to the east of the Muchea Fault, where geological units between the Wanneroo Member and Yarragadee Formation are absent.

The upper surface of Layer 6 (Fig. 109) is defined by the upper surface elevation of the Wanneroo Member (Fig. 48), and elsewhere by the lower surface elevation of Layer 5. In areas where the Wanneroo Member is absent, it is defined by the base of the superficial aquifer or the Kings Park Formation on the Swan Coastal Plain (Fig. 13).

Layer 7 is the lower layer of the Leederville aquifer and consists of the Mariginiup Member of the Leederville Formation. This layer extends over most of the model area and has a thickness ranging from 150 to 350 m in the northern Perth area (Fig. 53). Its thickness is commonly less than 150 m in the southern Perth area. Layer 7 is in direct contact with the overlying Layer 6. It is in contact with the underlying confining bed of the South Perth Shale over the Perth area, the Carnac Member on the Dandaragan Plateau and Swan Valley, and the Yarragadee Formation along the Pinjar Anticline.

The upper surface of Layer 7 (Fig. 110) is defined by the surface elevation of the Mariginiup Member (Fig. 51). In areas where the Mariginiup Member is absent, it is defined by the base of the superficial aquifer or the Kings Park Formation on the Swan Coastal Plain (Fig. 13).

5.2.5 Layer 8 — South Perth Shale and Carnac Member

Layer 8 is a confining bed and comprises the South Perth Shale and the Carnac Member of the Parmelia Formation. The South Perth Shale occurs over the Swan Coastal Plain and forms a regional confining bed with thickness ranging from 50 to 300 m (Fig. 56). It is absent in the central Perth area, in the coastal plain in the far northern part, and beneath the Dandaragan Plateau.

The Carnac Member lies mostly beneath the Dandaragan Plateau, where its thickness is up to 450 m. The Carnac Member is in direct contact with the overlying Leederville aquifer and the underlying Parmelia Sand aquifer.

The upper surface of Layer 8 is defined by the upper surface elevation of the South Perth Shale (Fig. 55) and the Carnac Member (Fig. 64), and the base of the superficial and Leederville aquifers (Figs. 13 and 88). Figure 111 shows the contour map of the surface of Layer 8.

5.2.6 Layer 9 — Parmelia Sand aquifer

Layer 9 consists of the Parmelia Sand aquifer, which is the sand bed in the lower Parmelia Formation. It exists mainly beneath the Dandaragan Plateau, and has a thickness up to 500 m near Gingin (Fig. 68). Layer 9 is in contact with overlying Carnac Member (Layer 8) and Mariginiup Member (Layer 7). The upper surface of Layer 9 (Fig. 112) is defined by the surface elevation of the Parmelia Sand Member, and by the lower surface of Layer 8 in the area where the Parmelia Sand Member is absent.

5.2.7 Layer 10 — Otorowiri Member

Layer 10 is composed of the Otorowiri Member of the Parmelia Formation and occurs mostly beneath the Dandaragan Plateau. Layer 10 forms a local confining bed with a general thickness ranging from zero to 50 m, although the thickness reaches 200 m near Gingin (Fig. 71). The upper surface of Layer 10 (Fig. 113) is defined by the surface elevation of the Otorowiri Member where it is present, and elsewhere by the lower surface of Layer 9.

5.2.8 Layers 11 and 12 — Yarragadee aquifer

The Yarragadee aquifer is a major regional aquifer in the Perth Region, and is represented by two model layers to account for the vertical hydraulic gradient and the fact that current abstraction is from the top 150 m of the Yarragadee aquifer.

The Yarragadee aquifer comprises the Gage Formation (Fig. 58), Yarragadee Formation (Fig. 73), and Cattamarra Coal Measures (Fig. 75). The Gage Formation is restricted to the Perth area. It is absent in the central Perth area, and at the northern boundary of the model. This formation is also absent beneath the Dandaragan Plateau, and has no direct contact with the Parmelia Formation. The Lesueur Sandstone of Triassic age occurs east of the Muchea Fault in the north-eastern corner of the study area (Diamond and Kay, 2001). The Lesueur Sandstone is poorly understood and it is considered as part of the Yarragadee aquifer (Layers 11 and 12) in the model.

The Yarragadee Formation extends over most of the model area, except at the southern boundary of the model. The thickness of the Yarragadee Formation mostly exceeds 1500 m in the northern part of the model and over 500 m in the southern part (Fig. 74). Towards the southern boundary of the model, the Yarragadee Formation is faulted out by the Mandurah and Serpentine Faults, and replaced by the Cattamarra Coal Measures.

Layer 11 represents only the top 150 m of the Yarragadee aquifer. The upper surface of Layer 11 (Fig. 114) is defined by surface elevations of the Gage Formation, the Yarragadee Formation, and the Cattamarra Coal Measures at the southern boundary.

Layer 12 represents the deep Yarragadee aquifer, which occurs beneath the entire model. The upper surface of Layer 12 (Fig. 115) is defined by the base of Layer 11.

The lower surface of Layer 12 is the base of the model, and is defined by the lower surface of the Yarragadee aquifer (Fig. 97).

5.3 Model boundaries

The model boundaries are shown in Figure 116. The Darling Fault forms the eastern boundary of the model and is assigned as a no-flow boundary for all the model layers. The model western boundary for the superficial aquifer is the coast (Fig. 1). This boundary is a constant head boundary where the water level is set at zero metres AHD and kept constant along the whole boundary. The coastal line was defined from DOLA topographic data as Microstation files (DGN file), with some additional lines that were created for ‘connectors’ to allow complete polygons to be constructed. The Microstation files were pre-processed using the GIS program to ensure topological correctness and to create centroid points for the island-type attribute information.

The model western boundary for the confined aquifers (Layers 3 to 12) is composed of a series of offshore faults that are located 10 to 20 km from the coastline (Fig. 8). In most cases, the first offshore fault was selected based on the assumption that both confined aquifers and confining beds extend continuously to the first fault. Groundwater flow patterns and aquifer properties were extrapolated to the offshore part of the confined aquifers based on the understanding of onshore hydrogeology.

The western boundaries of Layers 3 and 4, and Layers 8 to 12 are no-flow boundaries. The western boundaries of Layers 1 and 2 (the superficial aquifer) and Layers 5 and 7 (the Leederville aquifer) are constant head boundaries.

The northern boundary of the model is a straight line from east to west and is identical to the northern boundary of the Gingin Groundwater Area. The boundary combines a constant head boundary and a no-flow boundary. The constant head boundary allows groundwater to flow across the boundary from the north into the model domain. The no-flow boundary is present only along the western section of the northern boundary where groundwater flow is parallel to the boundary (Fig. 116).

The southern boundary comprises the Peel Inlet near Mandurah and Murray River to the east. The boundary is a no-flow boundary as it is nearly parallel to the regional groundwater flow direction.

There are several known faults within the model domain (Fig. 8). Although mapped, the hydraulic properties of the faults are poorly understood, and are thought to have minimal impacts on the groundwater flow, with the exception of the Serpentine Fault.

The Serpentine Fault extends from north to south along the south-eastern margin of the model area. Similarly to the Muchea Fault, the Serpentine Fault exists only in the formations older than the Leederville Formation. The fault separates the Yarragadee Formation in the west from the Cattamarra Coal Measures to the east. Although both formations are assigned to the Yarragadee aquifer, available water-quality data (Davidson, 1995), geological data (Davidson, 1995; Thorpe, 2003), and monitoring data (PPK, 2002) suggest that the fault is of low permeability and acts as a horizontal barrier within the Yarragadee aquifer.

5.4 Model parameterisation

Table 2 lists the estimated hydraulic conductivities of the geological units in the model area. Model parameters including horizontal hydraulic conductivity, vertical hydraulic conductivity, specific yield for unconfined aquifers, and storage coefficient for confined aquifers have been estimated through previous hydrogeological investigations (Davidson, 1995) and model calibrations. The model parameters were assigned initially to the model based on the distribution of geological units. Spatial distributions of the parameters in each layer are represented by parameter zones within which all parameters are constant.

Layers 1 and 2 have hydraulic conductivities ranging between 5 and 50 m/day for the sandy materials and between 100 and 1000 m/day for the limestone. The Becher Sand, Yoganup and Ascot Formations have low hydraulic conductivities (5–15 m/day). The Safety Bay Sand and Rockingham Sand have moderate to high hydraulic conductivities (10–30 m/day). The Tamala Limestone Sand, Bassendean Sand, and Gnangara Sand have high hydraulic conductivities (20–50 m/day). The hydraulic conductivity in the limestone area is highly variable and not well known. Its value has been derived through the model calibration. The average specific yield of the superficial aquifer is about 0.2. For the Bassendean Sand and Gnangara Sand it ranges between 0.2 and 0.3.

Layers 1 and 2 also contain Guildford Clay, which is a local confining bed and distributed along the river valley and foothills of the Darling and Gingin Scarps. The estimated horizontal hydraulic conductivities range between 0.01 and 1 m/day in areas comprising thick and dense clay, to 5 m/day in areas with interbedded sand lenses. The vertical hydraulic conductivity is about 10 per cent of the horizontal hydraulic conductivity. In areas where there is more than one geological unit, average horizontal and vertical hydraulic conductivity have been derived based on the methods described by Davidson (1995).

Layer 3 has horizontal hydraulic conductivities ranging between 1 and 10 m/day for the sandy materials on the Dandaragan Plateau, and between 1 and 5 m/day for the Mirrabooka Member in the Central Perth area. The aquifer specific yields range between 0.1 and 0.2 for unconfined aquifers of Layer 3, and the storage coefficient is in the order of 10^{-3} to 10^{-4} for confined aquifers of Layer 3 on the coastal plain. Hydraulic conductivities range between 20 and 30 m/day for the Rockingham aquifer.

Layer 4 is a confining bed and has hydraulic conductivities ranging from 10^{-4} to 10^{-6} m/day for areas comprising the Kardinya Shale and Lancelin Formation. In the area where the Kings Park Formation is present, hydraulic conductivities were obtained through the model calibration and range between 0.01 and 2.0 m/day. In other parts of the model where the above geological units are absent, the model uses hydraulic properties of the underlying geological material for Layer 4.

Layer 5 has horizontal hydraulic conductivities ranging between 1 and 5 m/day for the area comprising the Pinjar Member, and slightly higher (2–5 m/day) for the Henley Sandstone Member. The aquifer storage coefficient is in the order of 10^{-3} to 10^{-4}. Layer 6 is composed of the Wanneroo Member and has hydraulic conductivities ranging from one to 10 m/day. Layer 7 has a hydraulic conductivity ranging from 0.001 to one metre per day owing to shale content and cementation of the Mariginiup Member. Aquifer storage coefficient is in the order of 10^{-3} to 10^{-4}. Vertical hydraulic conductivities range between 0.01 and 1 m/day.

Layer 8 is a confining bed and has horizontal conductivities ranging between 10^{-4} and 10^{-5} m/day and storage coefficients between 10^{-5} and 10^{-6} for areas composed of either the South Perth Shale or the Carnac Member. In other parts of the model area where the above geological units are absent, the model uses hydraulic properties of the underlying geological material for Layer 8.

The Parmelia Sand aquifer in Layer 9 has horizontal hydraulic conductivities ranging between 0.1 and 2.0 m/day. Spatial distributions of the parameters for Layer 9 were derived by model calibration, and need to be verified. The Otorowiri Member of the Parmelia Formation in Layer 10 has horizontal hydraulic conductivities ranging between 10^{-5} and 10^{-6} m/day.

Layers 11 and 12 are the Yarragadee aquifer, which has horizontal hydraulic conductivities ranging from 1 to 5 m/day, and a storage coefficient of 10^{-4}. The aquifer has higher hydraulic conductivity over the central and coastal Perth area (the Yarragadee and Gage Formations), and lower hydraulic conductivity to the east of the model (the Cattamarra Coal Measures).

5.5 Hydrological processes

The Perth Region Aquifer Modelling System simulates major hydrological processes and calculates the water balance of the aquifer system. The hydrological processes represented in the model include groundwater recharge from rainfall, evapotranspiration, wetland and drainage interaction with groundwater, and groundwater abstraction. These hydraulic processes are represented by respective modules in Modflow, after generalisation and simplification of the actual physical processes.

The water balance calculation is a basic function of the model. It provides volumetric calculation of major flow components in the aquifer system, including recharge, evapotranspiration, drainage, vertical leakage, aquifer storage, and throughflow.

5.5.1 Groundwater recharge

Recharge to the superficial aquifer. Groundwater recharge to the superficial aquifer is the proportion of rainfall over the land surface that reaches the watertable. The amount of recharge depends on rainfall pattern (ie rainfall intensity, frequency, and duration), land surface condition including landuse and depth to watertable, and soil and geological conditions. Figure 81 shows a recharge map based on the calculation of chloride mass balance in groundwater, with comparison of chloride concentration in the rain water. The method is described by Davidson (1995).

Lower recharge rates range from zero to five per cent of the annual rainfall and are distributed along the eastern margin of the Swan Coastal Plain and river valleys where sediments are clayey. Higher recharge rates of up to 40 per cent characterise parts of the Gnangara and Jandakot Groundwater Mounds and urbanised areas. However, recharge rates in the dense pine plantation areas are low owing to interception and tree water use. A total of 18 recharge zones have been identified based on the recharge map (Fig. 81). The estimated net rainfall recharge to the superficial aquifer is given in Table 3.

The above recharge data were assigned to the model during calibration. They were altered with additional data from the vertical flux model. The vertical flux model has been developed using WAVES (Zhang and Dawes, 1998). This model simulates the water balances in the unsaturated zone and calculates daily vertical flux that reaches the watertable. The vertical flux model has been incorporated into the PRAMS saturated model.

Recharge to confined aquifers. Significant recharge to the confined aquifers takes place along the Pinjar Anticline in the central Perth area where confining beds are thin or absent; near the northern model boundary where the Yarragadee aquifer is near the land surface and in direct contact with the superficial aquifer; and on the Dandaragan Plateau where the Leederville and Yarragadee aquifer outcrops at the bottom of the valley where the Kardinya Shale has been eroded away.

Low to moderate recharge takes place in the form of vertical leakage through confining beds. The recharge to confined aquifers is represented by the vertical leakage in the model. The vertical leakage (Q) is calculated by the equation below and illustrated in Figure 117:

$$Q_{k+1/2} = CV_{k+1/2} * (h_{k+1/2} - h_k) \qquad (1)$$

where $CV_{k+1/2}$ is the vertical conductance of the confining bed between aquifers k and $k+1$, and h_{k+1} and h_k are the hydraulic heads of aquifers $k+1$ and k respectively.

5.5.2 Evapotranspiration

Evapotranspiration (EVT) in the study area is predominately related to climate, vegetation, land surface, the depth to watertable, and soil and geological conditions (Anson, 1985; Davidson, 1995). An EVT module in the Modflow (McDonald and Harbaugh, 1988) is described by the equation below and illustrated in Figure 118.

$$Q_{ET} = Q_{ETM} \frac{h - (h_s - d)}{d} \qquad (2)$$

where Q_{ET} is the calculated evapotranspiration rate, in metres per unit area; Q_{ETM} is the maximum evapotranspiration rate, which is estimated based on measured pan evaporation rate and a pan coefficient. d is the extinction depth beyond which evapotranspiration is negligible. On the Swan Coastal Plain, d is determined by the depth to watertable based on the assumption that plant roots are predominantly distributed above the watertable; h_s is the surface elevation at which maximum evapotranspiration takes place; h is the surface elevation where the actual evapotranspiration takes place. Figure 119 shows the calculated evapotranspiration rate. The EVT was assigned to the uppermost active cells.

5.5.3 Wetland and drainage interaction with groundwater

The wetlands on the Swan Coastal Plain consist of channel wetlands, and basin and flat wetlands. The channel wetlands or drainages include the Swan and Canning Rivers, creeks, and urban stormwater drains that are permanently or seasonally inundated. The basin and flat wetlands include lakes and swamps that are permanently or seasonally inundated or waterlogged. A Modflow drain module was used to represent the interactions between wetlands and groundwater.

Drainages. The Department of Water has gauging stations for monitoring flows in major drainages between Moora and Mandurah. Table 4 lists annual streamflow and baseflow data for the major drainages in the study area. Figures 120 and 121 show historical streamflow data. The streamflow is highly variable with the season, reaching peak levels in the winter fed by runoff over the catchment, and low levels in the summer where some drainages have no flow and others carry groundwater discharge as baseflow.

The average baseflow as percentage of streamflow is 58 per cent for all drainages in the study area. This indicates that most of the drainages are perennial and carry groundwater discharge as a main water source, especially during summer.

Figures 122–124 show the long-term streamflow data of selected drainages. The trends for most drainages are stable. However, the streamflow of the drainages that originate on the Dandaragan Plateau, including Gingin and Lennard Brooks in the north-eastern part of the study area, has increased in the last 10 years. In these drainages, the baseflow as percentage of streamflow is significantly higher (> 70%) than the average, and they are thus sourced predominantly by groundwater discharge. The increasing trends of drainage flow are probably due to significant land clearance on the Dandaragan Plateau that also causes rising groundwater levels in the area. Conversely, streamflow of drainages in the central and southern Perth areas have declined, probably owing to lower than average rainfall and increasing groundwater abstraction.

At the base of the Gingin and Darling Scarps, many of the smaller drainages dissipate on the sandy coastal plain. The large drainages, including Gingin and Lennard Brooks, commonly have base levels above the watertable in the east (the upstream section) and are losing streams in these areas. This relationship changes from the middle to lower section of the drainages to the west, where the base levels of the drainages are below the watertable. In these areas the drainages become gaining streams and carry groundwater discharge.

The interaction between the drainages and groundwater also changes with season. Figure 125 shows the difference in streamflow rate between the two Gingin Brook gauging stations. A positive value indicates that Gingin Brook gains water from groundwater discharge, and a negative value indicates that the brook loses water to the watertable. Streamflow difference is positive in the winter when the brook is gaining groundwater discharge as well as surface runoff, and becomes negative in the summer when the brook is losing water to the watertable, and through evaporation.

PRAMS uses a simplified drainage package that was developed in Modflow (McDonald and Harbaugh, 1988) to represent wetland and groundwater interaction. Figures 126–129 demonstrate the conceptualisation of the surface water and groundwater interaction. This approach is only applicable to drains that gain water from groundwater discharge (gaining streams).

Lakes and Swamps. Lakes and swamps occupy shallow depressions in the land surface and therefore are mostly shallow. Water in the lakes and swamps is only temporarily perched above the low-permeability sediments during heavy rainfall, and the hydraulic connection between lake and aquifer is established rapidly after a rainfall event. During summer, some shallow lakes become dry owing to evapotranspiration loss and declining regional water level, and also groundwater abstraction.

A land surface digital elevation model and wetland map (Hill et al., 1996) were used to define the location, geometry, and water level of wetlands. The current model treats the wetlands as the surface expression of the watertable and uses evapotranspiration zones to simulate higher evapotranspiration from the lake and swamp areas.

5.5.4 Groundwater abstraction

Groundwater in Perth is used as scheme supply reticulated to households and industry in Perth by Water Corporation, self-supply for agriculture, in particular horticulture, and various industries. Other functions include domestic, park and recreation uses by licensed private bores, and home garden use by unlicensed garden bores. Groundwater also supports extensive ecosystems in the region. Environmental water requirements (EWRs) are determined by identifying values and beneficial uses of groundwater-dependent ecosystems, and establishing water levels for their protection (Arrowsmith and Carew-Hopkins, 1994).

Because of changes in allocation processes and a lack of data management tools, historical groundwater abstractions have not been recorded systematically. Before the 1980s, only those private abstractions from confined aquifers were licensed. Table 5 lists a summary of groundwater abstraction data in the Perth Groundwater Area that have been documented in various sources.

Licensed entitlement and actual usage are not the same. Davidson (1995) employed a usage and licensed entitlement ratio of 0.8 for data between 1985 and 1995. Aquaterra (2001) and Yu (2002) used an average ratio of 0.92 to calculate the usage data from the licensed entitlement data. Water Corporation records monthly metering data for its production bores.

The PRAMS study area consists of the Perth Metropolitan Groundwater, and Gingin Groundwater Areas. The study area and groundwater management areas have the following relationship:

<table>
<tr><td rowspan="4">PRAMS study area</td><td rowspan="3">Onshore area or Perth region</td><td>Gingin Groundwater Area</td><td>Perth north</td><td>2996 (km^2)</td></tr>
<tr><td rowspan="2">Perth Metropolitan Groundwater Area</td><td>Perth central</td><td>1908 (km^2)</td></tr>
<tr><td>Perth south</td><td>2227 (km^2)</td></tr>
<tr><td>Offshore area</td><td>-</td><td>-</td><td>2000 (km^2)</td></tr>
<tr><td>Total area</td><td></td><td></td><td></td><td>9130 (km^2)</td></tr>
</table>

The Perth Metropolitan Groundwater Area covers Perth central and South areas between the southern boundary of the Gingin Groundwater Area and Mandurah of the Swan Coastal Plain, and includes the following groundwater areas:

Gnangara, Yanchep, Wanneroo, Swan, Mirrabooka, Gwelup, Perth, Jandakot, Cockburn, Rockingham, Serpentine, Murray (Nambeelup Subarea only),
and
South West Coastal (Mandurah Subarea only)

In 2004, a total of 600GL (gigalitres, or million kilolitres) of groundwater was abstracted from about 152 000 bores in both the Perth Metropolitan Groundwater and Gingin Groundwater Areas. Of this, 487GL was from the Perth Metropolitan Groundwater Area, and 113GL from the Gingin Groundwater Area, where water uses are mostly horticultural.

The following discussion is for the Perth metropolitan area only. The data for 2004 groundwater use are given in Figure 130 and Table 6.

Groundwater use – scheme supply. The Water Corporation supplied 158GL of groundwater to the Perth Region in 2004. About 40 per cent of water was extracted from the superficial aquifer, and 60 per cent from the confined Mirrabooka (3%), Leederville (27%) and Yarragadee (30%) aquifers. The main water uses include domestic, institutional, commercial and industrial uses, with the domestic sector accounting for 65 per cent of the scheme groundwater supply. Figure 131, which gives historical scheme groundwater supply by Water Corporation, shows that scheme groundwater supply increased from 59GL in 1980 to 158GL in 2004 at an average growth rate of about 8GL/year.

Groundwater use – licensed self-supply. Groundwater for licensed self-supply is drawn from private bores. A licence is required for bores pumping groundwater from the confined aquifers, and for those pumping from the superficial aquifer to irrigate an area of garden larger than 0.2 hectares. In 2004, the total licensed entitlement for licensed self-supply was 236GL/year for the Perth metropolitan area. The usage of licensed self-supply is estimated at 217GL/year using the usage/entitlement ratio of 0.92.

About 85 per cent of groundwater was extracted from the superficial aquifer and 15 per cent from the confined Mirrabooka (1%), Leederville (9%) and Yarragadee (5%) aquifers. Figure 132 and Table 6 show that the horticultural and agricultural use accounts for 46 per cent of the total licensed groundwater self supply, followed by industry and services use (19%), park and recreation use (19%), and domestic and other uses (16%).

Figure 133 shows an estimated historical self-groundwater supply by licensed private bores. The number of private licences reached 1000 in 1981, and near 10 000 in 1993. This number stabilises over the period 1996–99, followed by a rapid growth from 1999 to 2004. For the last 10 years, the average growth in the number of licences has been about 780 new licences per year. Total licensed private abstraction followed a trend similar to that of the total number of licences, increasing from 127GL in 1992 to 217GL in 2004. Total private abstraction growth has been at about 8GL/year for the last 12 years.

Groundwater use – unlicensed home garden use. Many Perth residents enjoy the availability of good quality shallow groundwater in their backyard. No licence is required for constructing bores for garden use in the Perth Region. Garden bores are used mainly for watering gardens; minor uses include domestic water for households and livestock. About 60 per cent of owners use automatic reticulation, and 36 per cent manual reticulation. An average garden bore pumps about 800kL per year in the Perth metropolitan area (WRC, 2000). In 2003–04, about 140 000 households, or 30 per cent of the total households in Perth, had garden bores and abstracted a total of 112GL/year. Almost all garden bores pump water from the superficial aquifer.

Garden bore installation is influenced by factors such as depth to watertable, geology, water quality, cost of scheme water and bore installation, and lot size. Over the last 10 years, the total number of garden bores increased by about 3000 new bores per year, and groundwater abstraction increased by about 2 to 3GL/year (Fig. 134).

Figure 135 shows an estimated total groundwater use that increases from 266GL/year in 1992 to 355GL/year in 1999, at an average rate of 13GL (5%) per year. However, total water use reached 487GL/year in 2004, increasing 26GL (7%) per year from 1999 to 2003.

Groundwater use by areas. The Perth metropolitan area includes Perth central (Gnangara Mound) and Perth south (including Jandakot Mound).

Perth central is bounded by Gingin Brook to the north and the Swan River to the south, and covers an area of 1908 km^2. In 2004, a total of 336GL of groundwater was extracted by Water Corporation (151GL or 45%), licensed private bores (127GL or 38%), and home garden bores (58GL or 17%). Of the total abstraction in the Gnangara Mound area, about 67 per cent was from the superficial, two per cent from the Mirrabooka, 16 per cent from the Leederville and 15 per cent from the Yarragadee aquifers (Fig. 136 and Table 7).

Perth south is bounded by the Swan River to the north and Peel Inlet to the south, and covers an area of 2227 km^2. In 2004, a total of 151GL of groundwater was extracted by licensed private bores (90GL or 60%), home garden bores (54GL or 35%), and Water Corporation (7GL or 5%). Of the total abstraction in the Jandakot Mound area, about 132GL or 87 per cent was from the superficial, 8GL or 5 per cent from the Leederville and 11GL or 7 per cent from the Yarragadee aquifer (Fig. 137 and Table 8).

Groundwater use by aquifers. In 2004, about 360GL (74%) of groundwater abstraction was from the superficial (Fig. 130 and Table 6), 6GL (1%) from the

Mirrabooka, 61GL (13%) from the Leederville and 60GL (12%) from the Yarragadee aquifers. However, the abstractions by Water Corporation and private bores are from different aquifers. About 85 per cent of the licensed private abstraction, and almost 100 per cent of the home garden use are from the superficial aquifer; compared with 40 per cent of Water Corporation abstraction from the superficial aquifer.

Unlicensed home garden bores are represented as an areal sink. The water use was represented by the distribution of bore density in 26 groundwater areas in the model. The average water use by a garden bore is estimated at 800kL per year. The annual water use is considered to fall within the six dry months from December to May, assuming that bore water use is negligible in the winter months.

The Water Corporation production bores (230) and the licensed private bores (15 555) are represented by a well package in Modflow and are defined by the following data:

- *Location*. Surveyed coordinates and elevation of a drawpoint, or centroid location of a property that has a water licence.
- *Aquifer.* Either by the known screen interval, or by interpreted aquifer types.
- *Abstraction data.* Water Corporation records the monthly metering data. Licensed private use is partitioned into monthly use based on a time function recommended by the PUWBS (Cargeeg, 1987). A scaling factor of 3 per cent was used as an annual increment to establish the historical water use. However, a scaling factor based on the historical water use in each groundwater subarea is used to replace the single arbitrary 3 per cent scaling factor.
- *Recycling water.* Most of the licensed abstractions are for irrigation purposes. It is assumed that 20 per cent of the licensed abstraction or allocation returns to the watertable. Further studies are needed to improve the understanding of irrigation on the Swan Coastal Plain.

5.6 Limitations of the model

5.6.1 Geological and hydrogeological uncertainty

The superficial aquifer

The superficial aquifer has been mapped collectively in this study. However, the distribution and deposition processes are not fully understood, especially in the foothill areas along the Gingin and Darling Scarps. The major units including the ‘coffee rock’ and Guildford Clay have not been mapped for assessment of groundwater and wetland interactions. There is also a lack of detailed information around the wetlands, where acidic sulfate soils and wetland impact studies require site-specific soil and geological information.

The coastal Tamala Limestone comprises highly variable limestone with cavities, lime sand lenses, and fresh limestone. The poorly understood hydrological processes including recharge, throughflow, hydraulic gradient, and groundwater discharge at the saltwater interface, are highly variable.

Kings Park Formation

The Kings Park Formation consists, from the top, of Mullaloo Sandstone, Kings Park Member, and Como Sandstone (Fig. 16). This formation has been intercepted within all three Yarragadee bores drilled by the Water Corporation in 2001–2002. Available data indicate that this unit may be distributed extensively offshore along the Perth Metropolitan coastline as well as along the downstream section of the Swan and Canning Rivers. The extent of the Kings Park Formation, especially in the offshore area, is not clear.

Although the Kings Park Formation has not been considered as a major aquifer previously, drilling of the three new Yarragadee bores indicated that the formation contains thick sandstone beds. The implication of these findings on the water resource calculation, groundwater and river interaction, and saltwater intrusion would be significant and needs further study.

Geological structure and offshore faults

The geological structure, especially for the deeper formations, has not been well defined owing to lack of data. The deeper geology beneath the Dandaragan Plateau was mapped based on concepts derived from offshore geological interpretation.

The offshore area was mapped based on the simple extrapolation of onshore geology and a limited number of petroleum drilling sites. The hydraulic characteristics of the deeper aquifers and faults are unknown. It is not clear whether the offshore faults constitute horizontal aquifer barriers of lower permeability.

5.6.2 Wetland and groundwater interactions

PRAMS uses a simplified drainage package that was developed in Modflow (McDonald and Harbaugh, 1988) to represent wetland and groundwater interactions. This approach is applicable only to drains that gain water from groundwater discharge (gaining streams). However, streamflow data indicate that the relationship between the drainage and groundwater changes with location and time.

The hydraulic connection between drainages and groundwater has impacts on the local groundwater flow pattern. In the upstream area of Gingin Brook on the coastal plain, water levels in confined aquifers at monitoring bores AM6 (Yarragadee) and AM6A (Leederville) were about 48 m AHD in 1992, but have fallen significantly in recent years as a result of significant increases in private abstraction (Fig. 138). The water level in the superficial aquifer is 10 m higher than that of the confined aquifers, and the long-term trend is stable (Fig. 139). The nearby Gingin Brook has an elevation of about 60 m AHD, and the streamflow has been stable in recent years (Fig. 122). It has been difficult to calibrate the model in this area.

5.6.3 Hydrogeological and model boundaries

Hydrogeological and model boundaries are important constraints to groundwater flow and recharge. The natural hydrogeological boundaries have been used for the model boundaries. However, the characteristics of the hydrogeological boundaries are largely unknown owing to fewer investigations at the marginal areas where access is difficult and hydrological processes complicated. Such areas are likely to be neglected.

The Darling Fault forms the eastern boundary of the model. At the base of the Gingin and Darling Scarps, many of the small drainages that dissipate on the sandy coastal plain have not been included in the model. However, the potential effect of these drains on groundwater was taken into account through setting up the recharge zones in the area. Higher recharge rates were used to account for the drainage that enters the aquifer through vertical infiltration along the base of the Gingin and Darling Scarps. The detailed hydrological processes along the foothills and interactions with groundwater need further investigation.

The western boundary of the model for the confined aquifers comprises a series of offshore faults that are located 10 to 20 km from the coastal line. In most cases, the first offshore fault was selected based on the assumption that both confined aquifers and confining beds extend continuously to the first fault. The hydraulic characteristics of the deeper aquifers and faults are unknown.

The southern boundary comprises the Peel Inlet near Mandurah and Murray River to the east. The boundary is a no-flow boundary as it is nearly parallel to the regional groundwater flow direction. However, there are concerns about the potential impact of abstraction from the Yarragadee aquifer in the Murray Groundwater Area located about 20 km south of the model southern boundary. The abstraction has affected the water level in monitoring bores AM68, AM69 and AM70, and therefore changed the regional groundwater flow pattern. Since 1998, the previous westerly flow has become south-westerly. The Murray Groundwater Area may need to be included in a future model update.

There are several known faults within the model domain (Fig. 8). Although mapped, these faults are hydraulically poorly understood, and are thought to have minimal impacts on the groundwater flow, with the exceptions of the Muchea and Serpentine Faults.

The Muchea Fault extends from north to south along the north-eastern margin of the Dandaragan Plateau. The fault extends from below the Leederville Formation to the deeper formations. The effect of this fault on the groundwater flow in the

Yarragadee aquifer is not known. Geological materials on both sides of the fault are either the Yarragadee Formation or the Cattamarra Coal Measures, and both have been assigned to the Yarragadee aquifer. The south-westerly groundwater flow in the Leederville and Yarragadee aquifers may not be affected by the fault.

5.6.4 Knowledge and data gaps

Gaps in knowledge and data include the lack of proper testing for hydraulic properties of geological units, and the poor quality of historical data. The main problem is a paucity of groundwater-usage data from licensed private bores.

The licensed private and Water Corporation bores are represented by a well package in the PRAMS model. The bore location (easting and northing of the drawpoint), aquifer type, allocation amount, starting and expiry dates, and water use types are used to define the bores in PRAMS. Water Corporation is able to provide details of its production bores and monthly water use data for recent years. The licensed private bore data are stored in the Water Resource Licensing (WRL) database and administered by the Department of Environment's Regional Support Branch. The database shows details of a licensed bore with the latest licensed entitlement amount. PRAMS generated time-series data for the licensed private bore entitlement from 1980 and 2003, using a scaling factor based on historical licensed entitlement data.

The licensed entitlement data in PRAMS have been updated every six months. Each time, the modelling team makes a data request to the WRL team and Water Corporation. The dataset is then evaluated by the modelling team before it is entered into the PRAMS database.

6 Conclusions and recommendations

6.1 Conclusions

This report presents a study of geology, hydrogeology and groundwater resources in the Perth Region. The study incorporates new data collected since the publication of GSWA Bulletin 142 (Davidson, 1995), which has become a key reference for groundwater resource investigation and management. In the course of the study, a conceptual hydrogeological model that was used for the development of the Perth Region Aquifer Modelling System has been developed, and the following findings and conclusions have been obtained.

6.1.1 Geology

The study, which covers an area of 9100 km^2, including over 2000 km^2 offshore, is about twice the area covered by Davidson (1995). Perth north (Gingin) and the offshore area were newly mapped. This extended mapping has produced a full picture of geology and hydrogeology for the Swan Coastal Plain as well as the Dandaragan Plateau. It has also provided information for groundwater resource assessment in the Gingin Groundwater Area, where there is significantly increasing groundwater use.

New bore data from about 100 bores have been incorporated, and much of the geology from Davidson (1995) reinterpreted. Modern mapping and geological modelling tools, including GIS and GMS, have provided a state-of-the-art three-dimensional interpretation and visualisation.

The Carnac, Parmelia Sand, and Otorowiri Siltstone Members of the Parmelia Formation have been defined and mapped. It is also the first time that the base of the Yarragadee Formation has been mapped. These new maps provide a consistent geological structure for the entire study area, both inland and offshore.

6.1.2 Hydrogeology

The study has produced a watertable contour map covering both the Swan Coastal Plain and the Dandaragan Plateau. This map has been useful for estimating the depth to watertable, recharge studies, and assessing the impact of land and water use on the groundwater-dependent systems, in particular in foothill areas.

The study has also identified a new aquifer, namely the Parmelia Sand aquifer in the Parmelia Formation. The aquifer is a local confined aquifer beneath the Dandaragan Plateau and commonly contains saline water. The study also provided estimates of hydraulic properties for the 23 geological units that were grouped into the superficial, Mirrabooka, Leederville and Yarragadee aquifers, and several regional confining beds.

A map of rainfall recharge to the superficial aquifer has been produced. The study also found that the relationship between drains and groundwater is seasonally dependent, based on streamflow and baseflow analyses.

Around 1000 groundwater monitoring bores were assessed and selected for monitoring the watertable and the superficial, Leederville and Yarragadee aquifers. Groundwater contour maps and recharge/discharge relationships have been updated and extended to Perth north (Gingin) and the offshore area.

6.1.3 Groundwater use

The study has produced an estimate of the current and historical groundwater abstraction, and provided details and statistics of groundwater use by various industries and users, either by management area or by aquifer. The ratio of groundwater usage to licensed entitlement has also been estimated and found to be significantly higher than in the 1990s.

6.1.4 Conceptual model

The study established a 12-layer conceptual hydrogeological model that represents seven aquifers and five confining beds to a depth of 3000 m, and major hydrological processes have been described. The PRAMS numerical model has been developed based on the conceptual model and described in other volumes of the PRAMS report series (CyMod Systems, 2004).

6.2 Recommendations

The following recommendations have been made for improvement of geological understanding and model development.

6.2.1 Improvement to monitoring network

The groundwater monitoring network, especially the artesian monitoring bores, was established in the 1970s. It is recommended that the Department upgrades and improves the existing monitoring network, and installs additional monitoring bores to fill data gaps. The monitoring frequency should also be enhanced.

6.2.2 Investigation programs

The following investigations are recommended to improvement the hydrogeological conceptual models.

North Gnangara Groundwater Mound including Yeal Swamp

There is lack of understanding of the hydrogeology in the area, and especially of the relationship between Yeal Swamp and groundwater levels in the superficial aquifer.

Interaction between wetlands including Gingin Brook and groundwater at the foothills of Gingin Scarp

This investigation will improve the understanding of wetlands and groundwater interaction at the foothills. At present, all wetlands in the model are considered as groundwater-dependent wetlands or flowthrough lakes, although there are wetlands situated well above the regional watertable. The hydraulic characteristics of the wetlands and their connection with the groundwater system is not clearly defined. Figure 140 represents a local conceptual model that shows the following processes:

- The upstream section of Gingin Brook feeds water to the local superficial aquifer and generates a local groundwater mound.
- The wetlands along the foothills of the Gingin Scarp receive runoff from the Dandaragan Plateau, thus forming a recharge area to the superficial aquifer and maintaining a significant groundwater mound and associated head difference between the superficial and confined aquifers.
- A significant hydraulic gradient exists in the superficial aquifer resulting from the presence of low- permeability clayey materials such as Guildford Clay.

It is recommended that a network of investigation bores is drilled to the different sections of the superficial aquifer and to the top section of the Leederville aquifer. Pumping tests and hydraulic tests of sediments should be carried out to determine the hydraulic connection between the wetlands and aquifer. A local groundwater model should be developed to simulate hydrological processes, especially groundwater recharge.

Aquifer connectivity and recharge to the confined aquifer in the center of the Gnangara Groundwater Mound

At the centre of the Pinjar Anticline the regional confining beds (Kardinya Shale and South Perth Shale) are not present and the superficial, Leederville and Yarragadee aquifers are in direct contact.

It is recommended that exploration bores be drilled to identify the stratigraphy and the location of a hydraulic window to the Yarragadee aquifer. Sediment and water sampling, geophysical logging, and pumping tests should be carried out to provide information on aquifer connectivity and hydraulic properties of the aquifers.

Kings Park Formation

The Kings Park Formation is distributed along a deep erosion valley that cuts through the confined aquifers. It is important to understand the distribution and hydraulic properties of the Kings Park Formation onshore and offshore. This will assist in the assessment of water resource potential of the formation, and the risk of saline water intrusion. It is recommended that exploratory bores be drilled to investigate the geology and water quality of the Kings Park Formation. A three-dimensional geological model should be developed to estimate the distribution of the formation and its hydraulic connection with aquifers.

Appendix A Figures

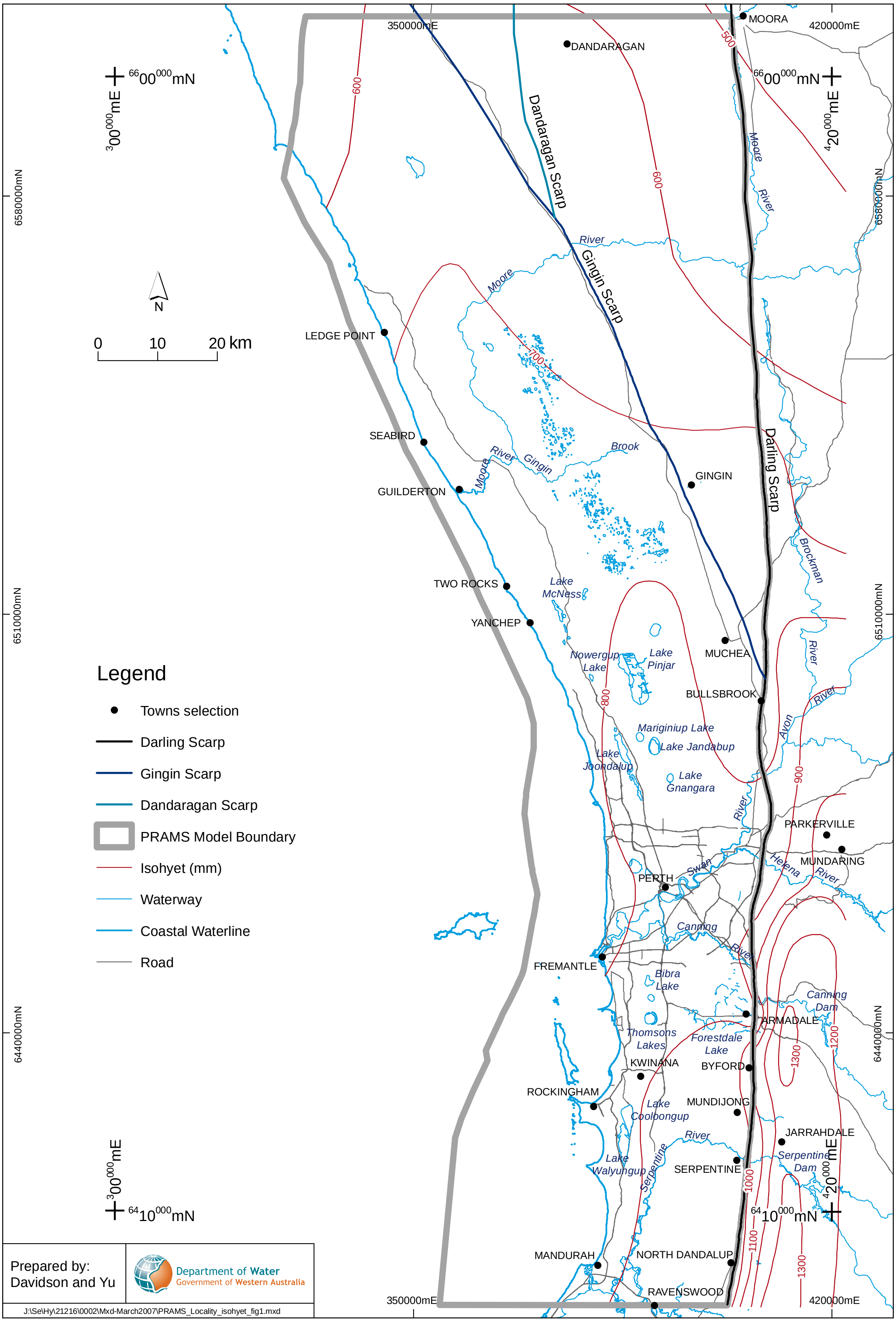


Figure 1 Locality map and rainfall isohyet

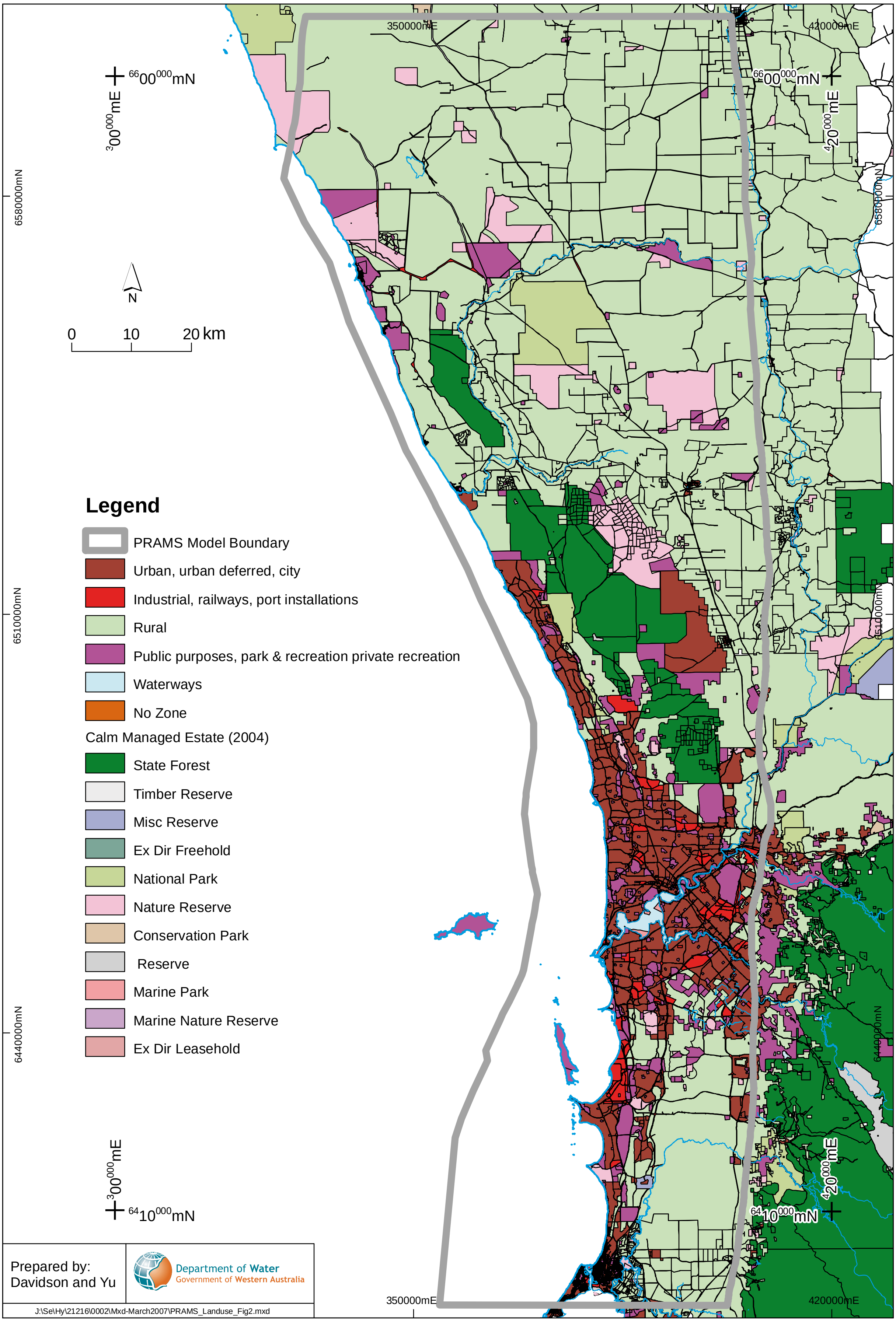


Figure 2 Landuse

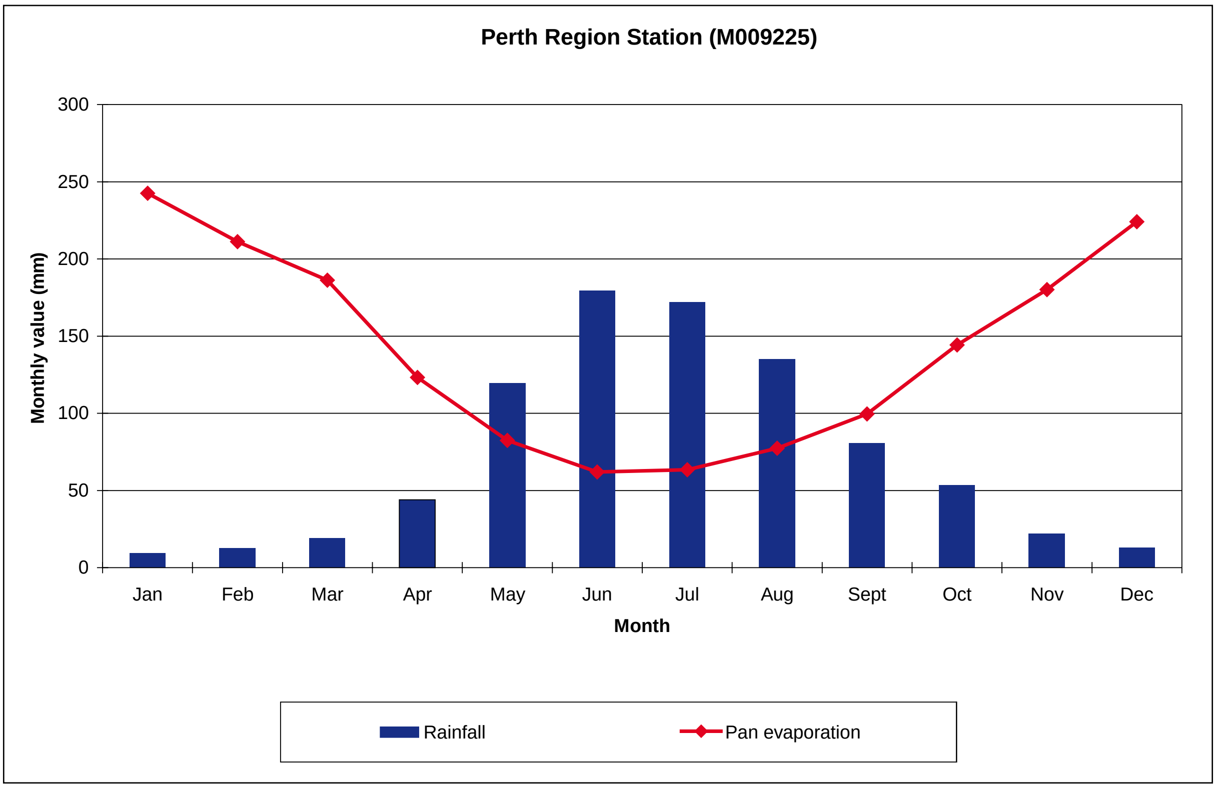


Figure 3 Perth average monthly rainfall and evaporation

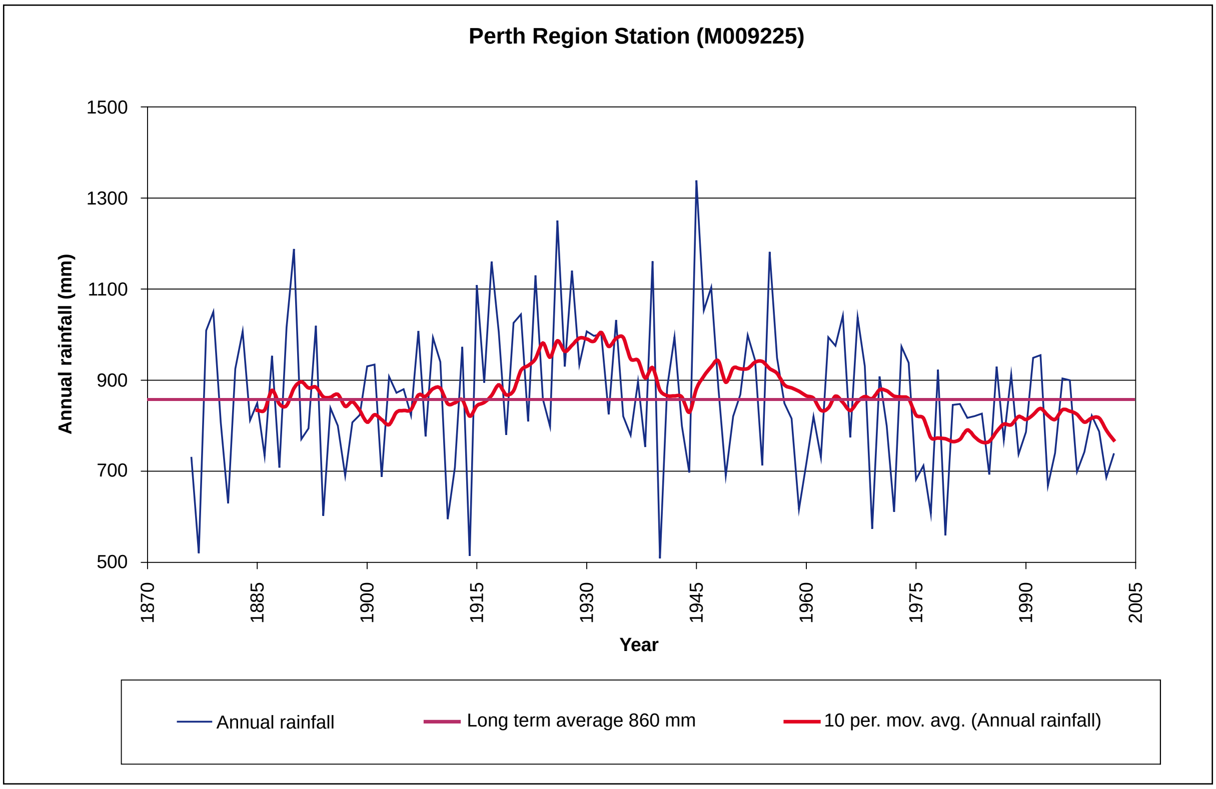


Figure 4 Perth annual rainfall

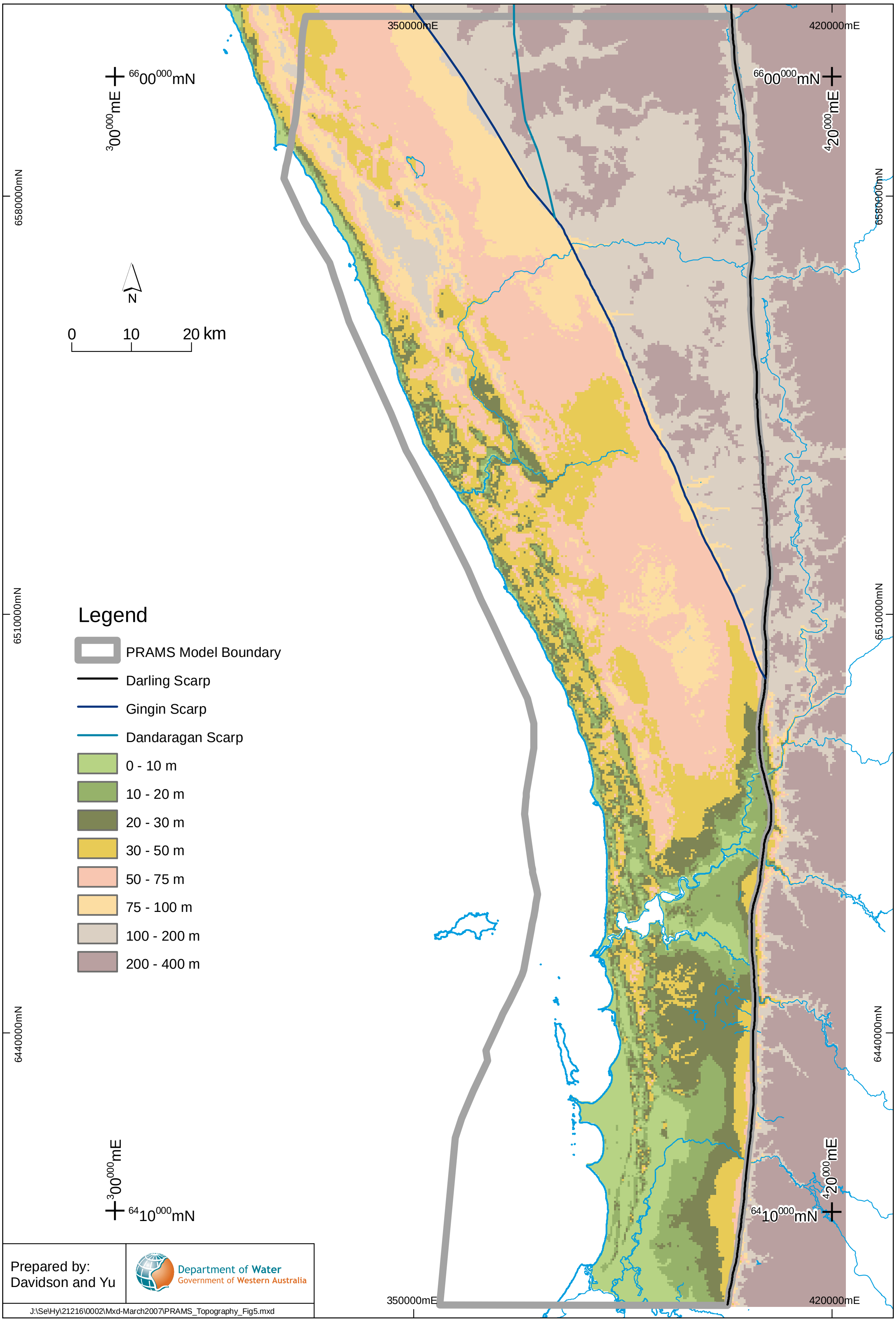


Figure 5 Generalised topography

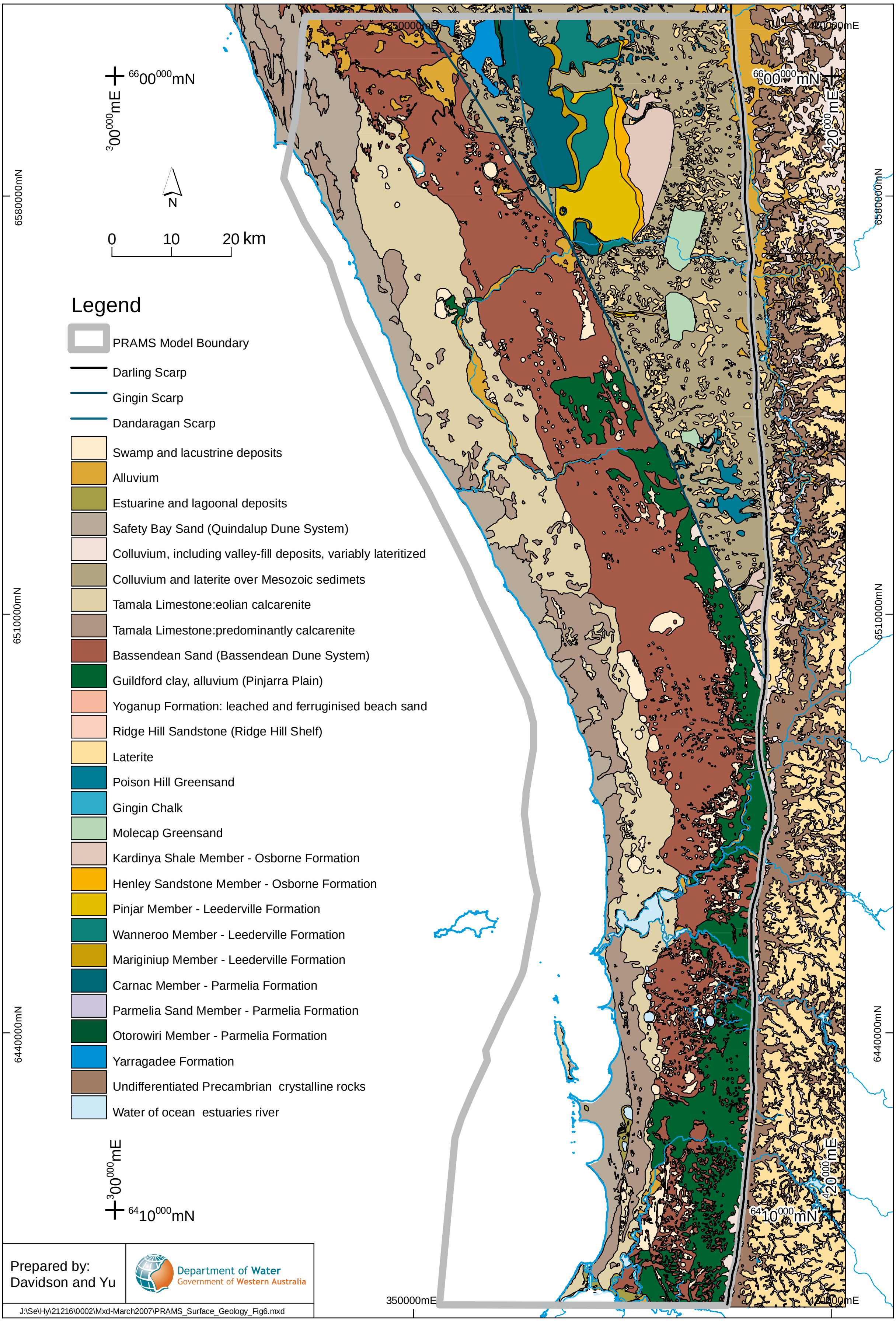


Figure 6 Surface geology and geomorphology; generalised

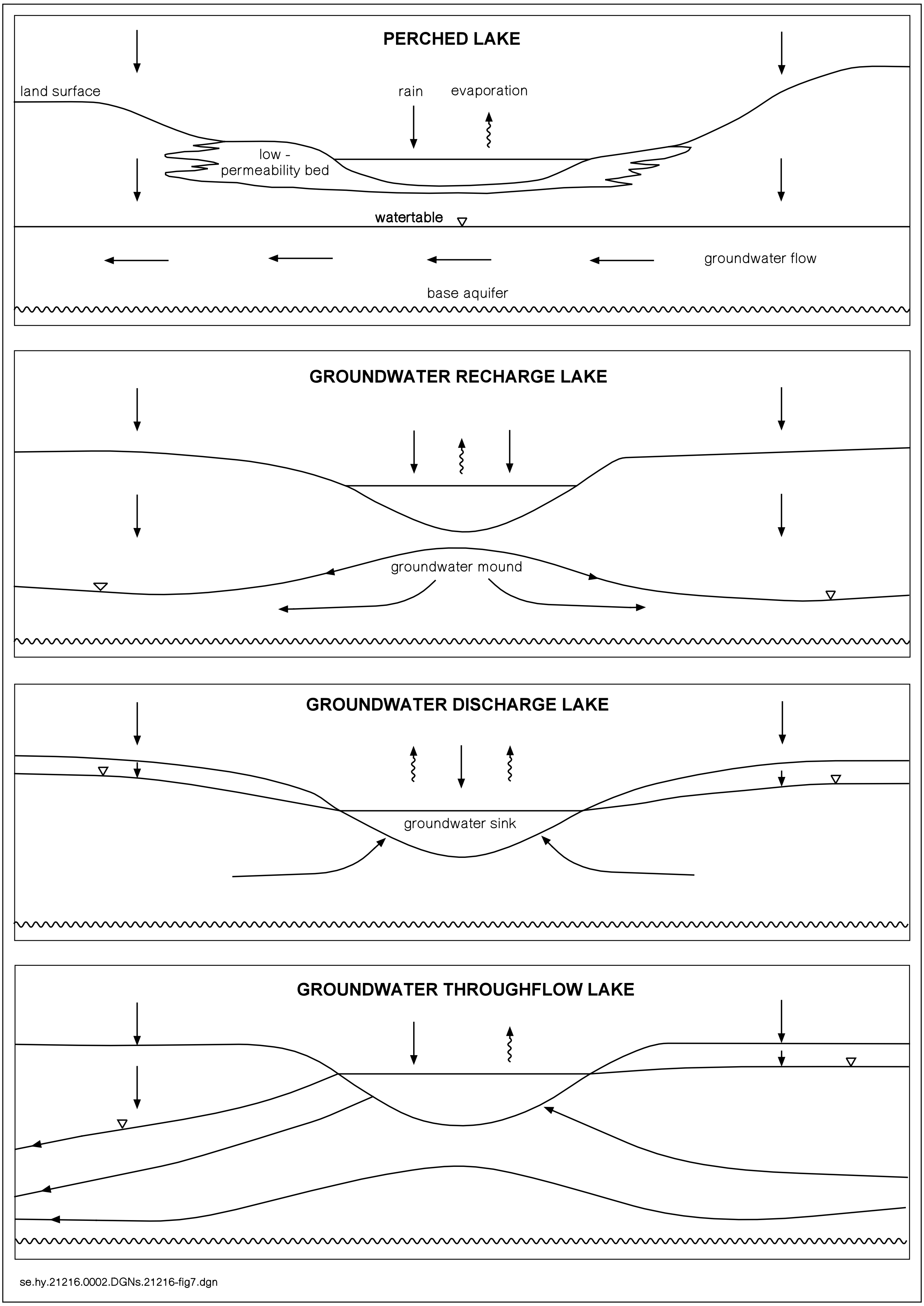


Figure 7 Groundwater flow associated with lakes (after Davidson 1995)

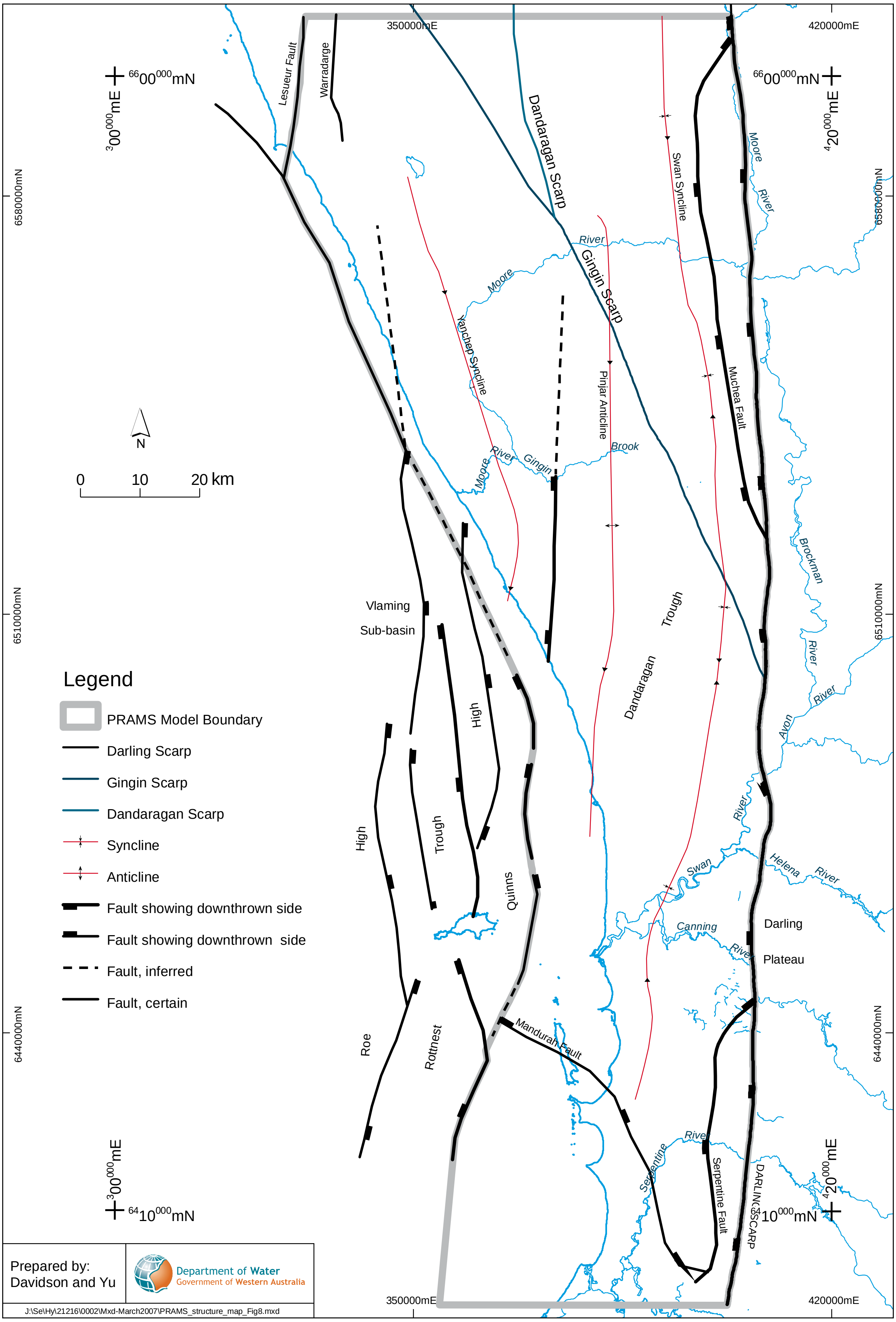


Figure 8 Structure map

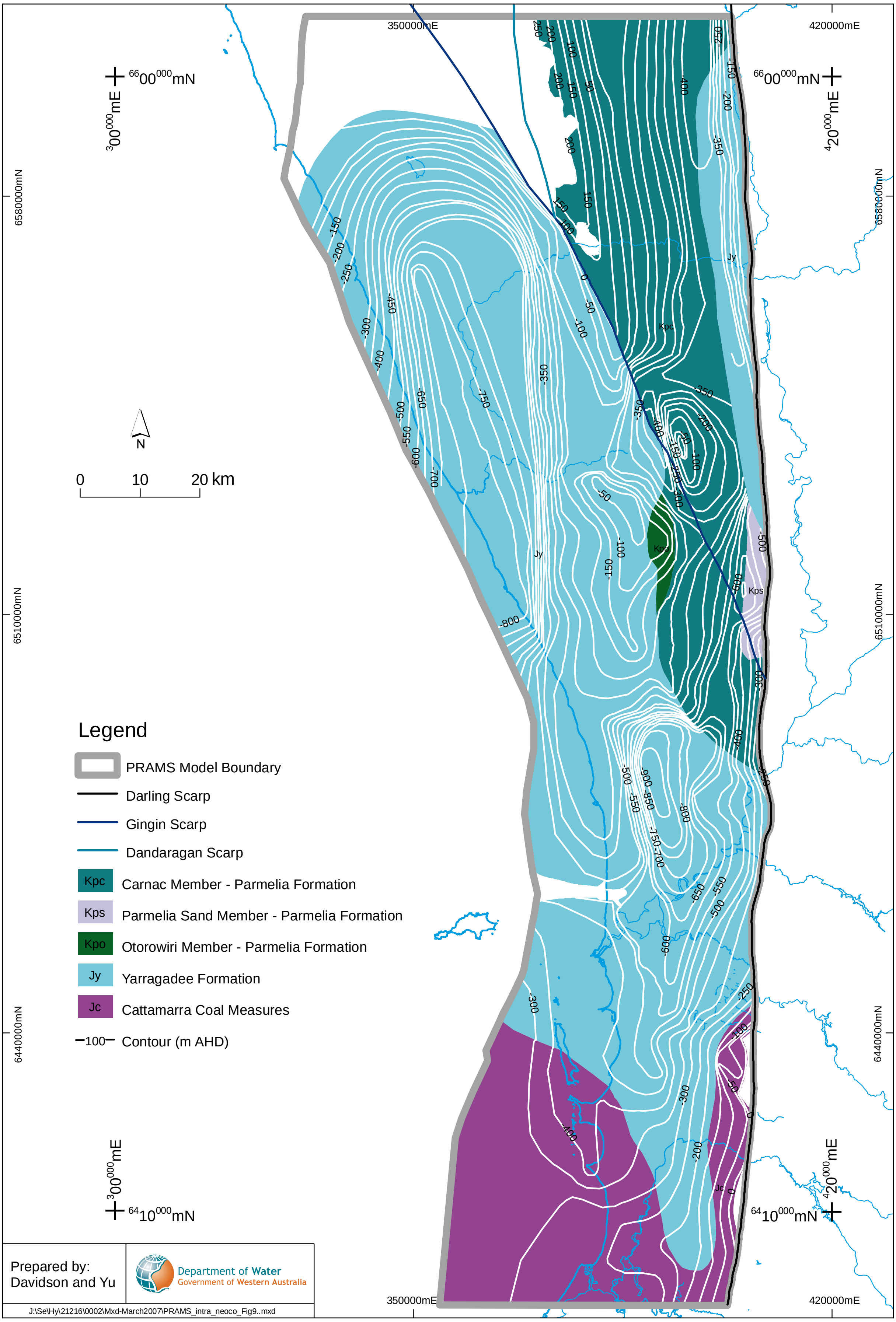


Figure 9 Intra-Neocomian unconformity surface showing strata subcrop

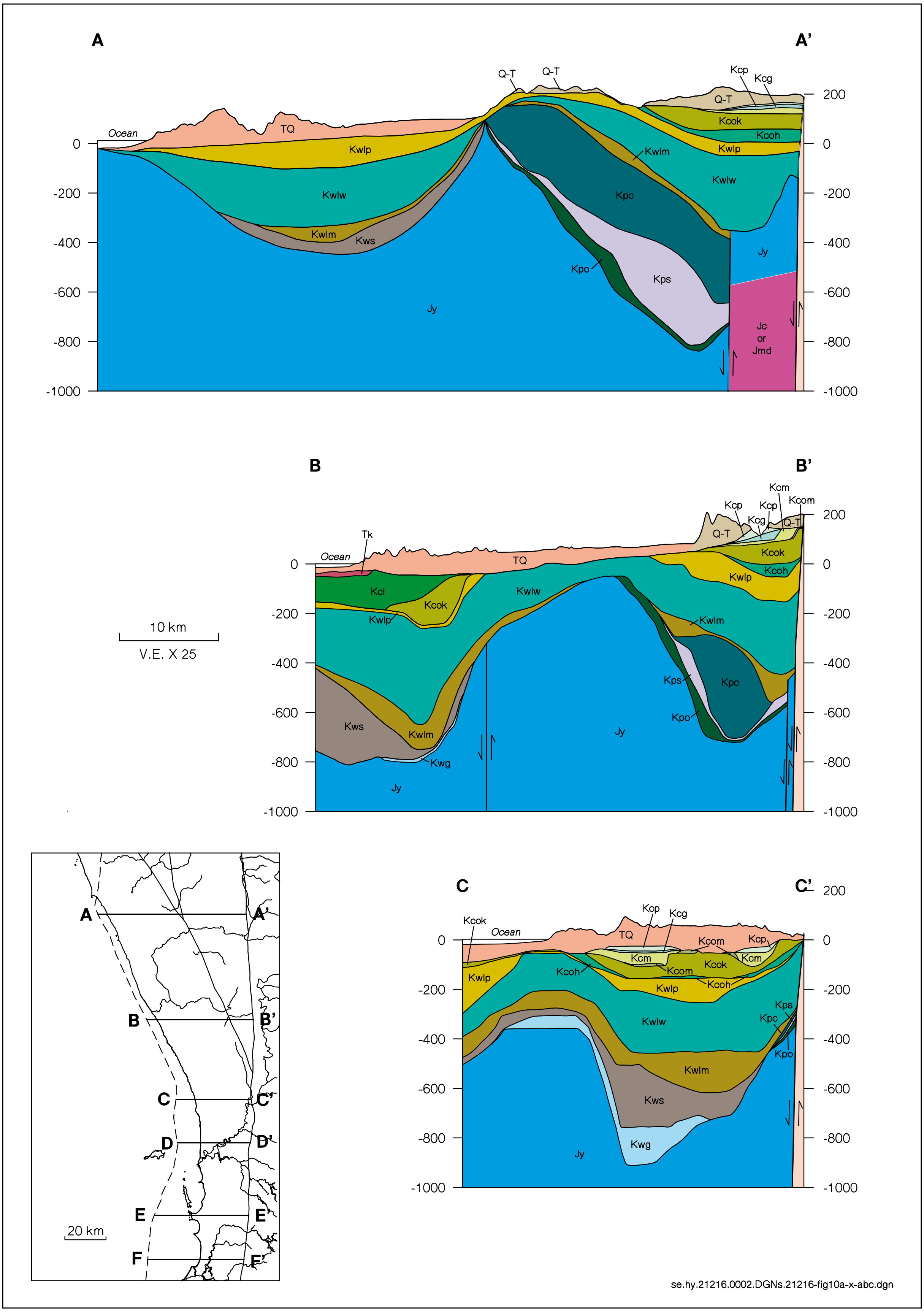


Figure 10a Geological sections showing stratigraphic relationships of Cainozoic and Mesozoic formations

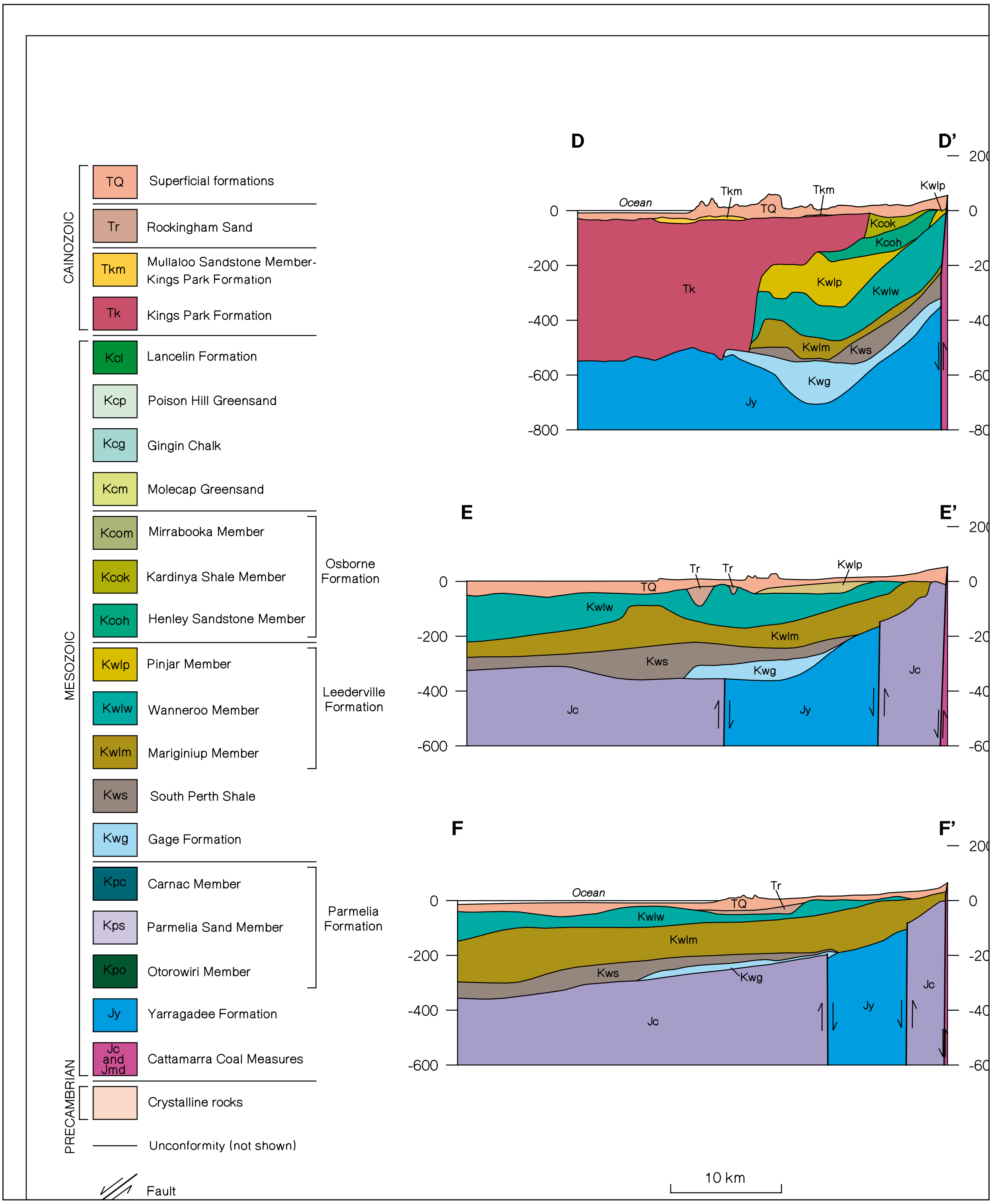


Figure 10b Geological sections showing stratigraphic relationships of Cainozoic and Mesozoic formations

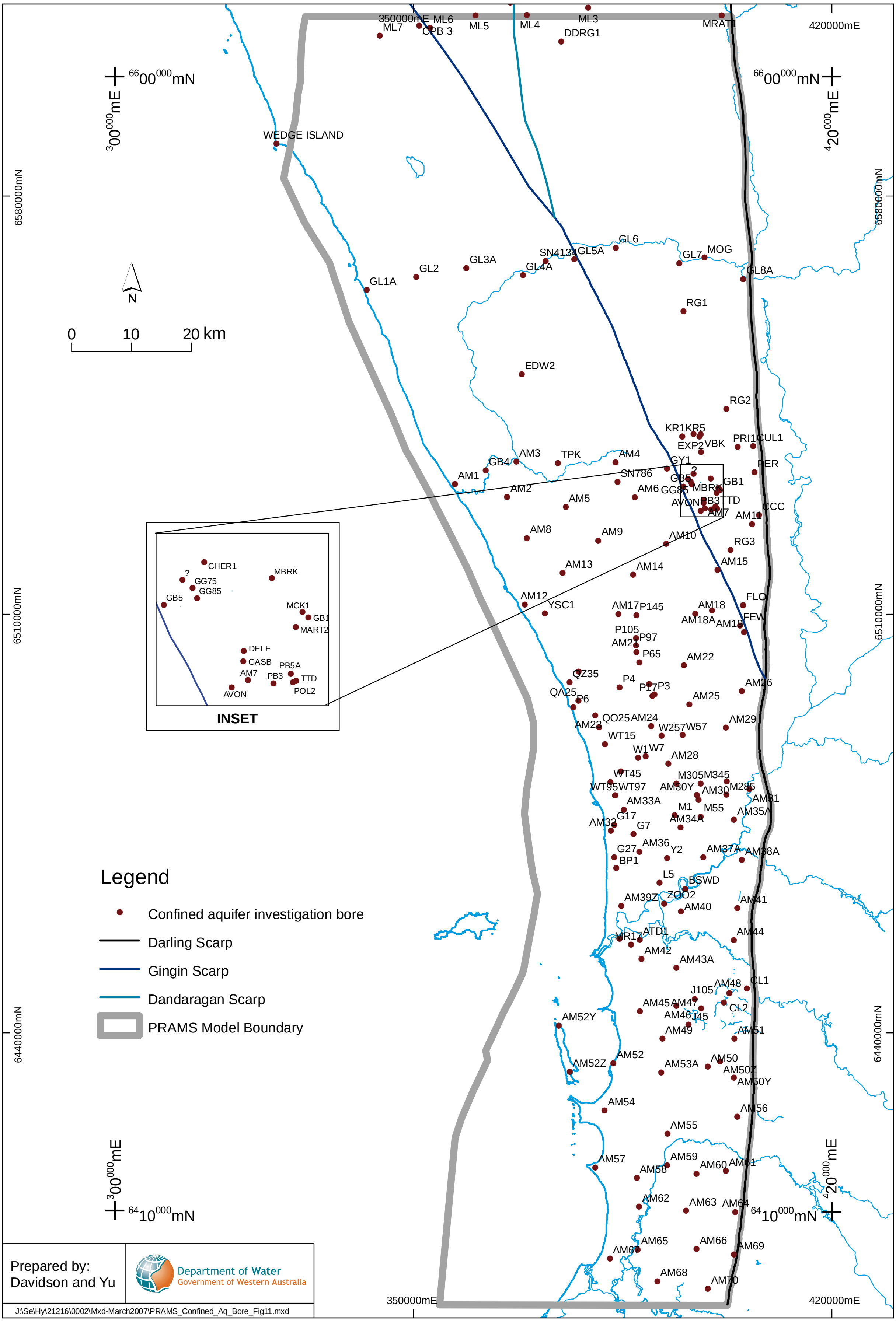


Figure 11 Confined aquifer investigation and production bores

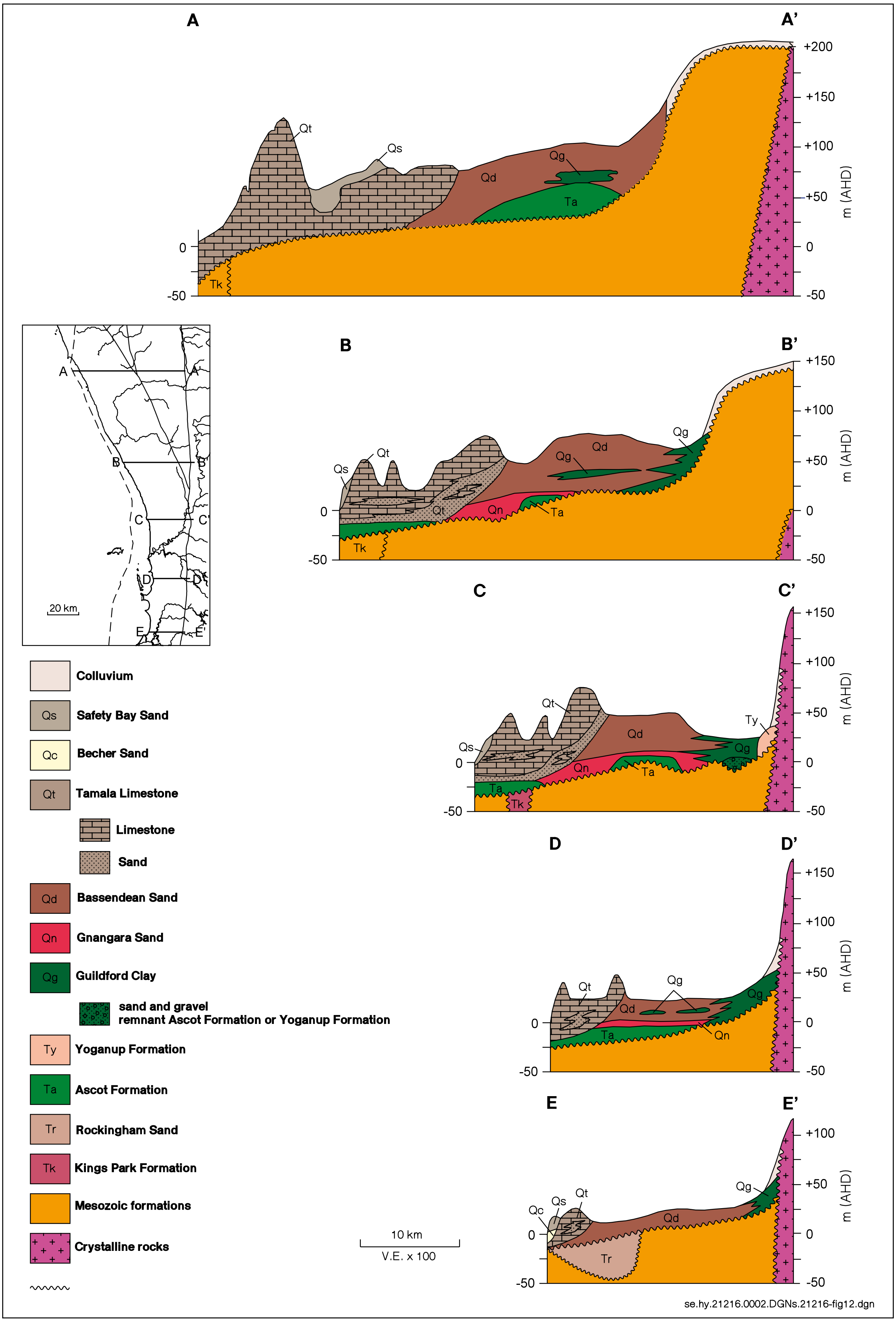


Figure 12 Geological sections showing stratigraphic relationships of superficial formations

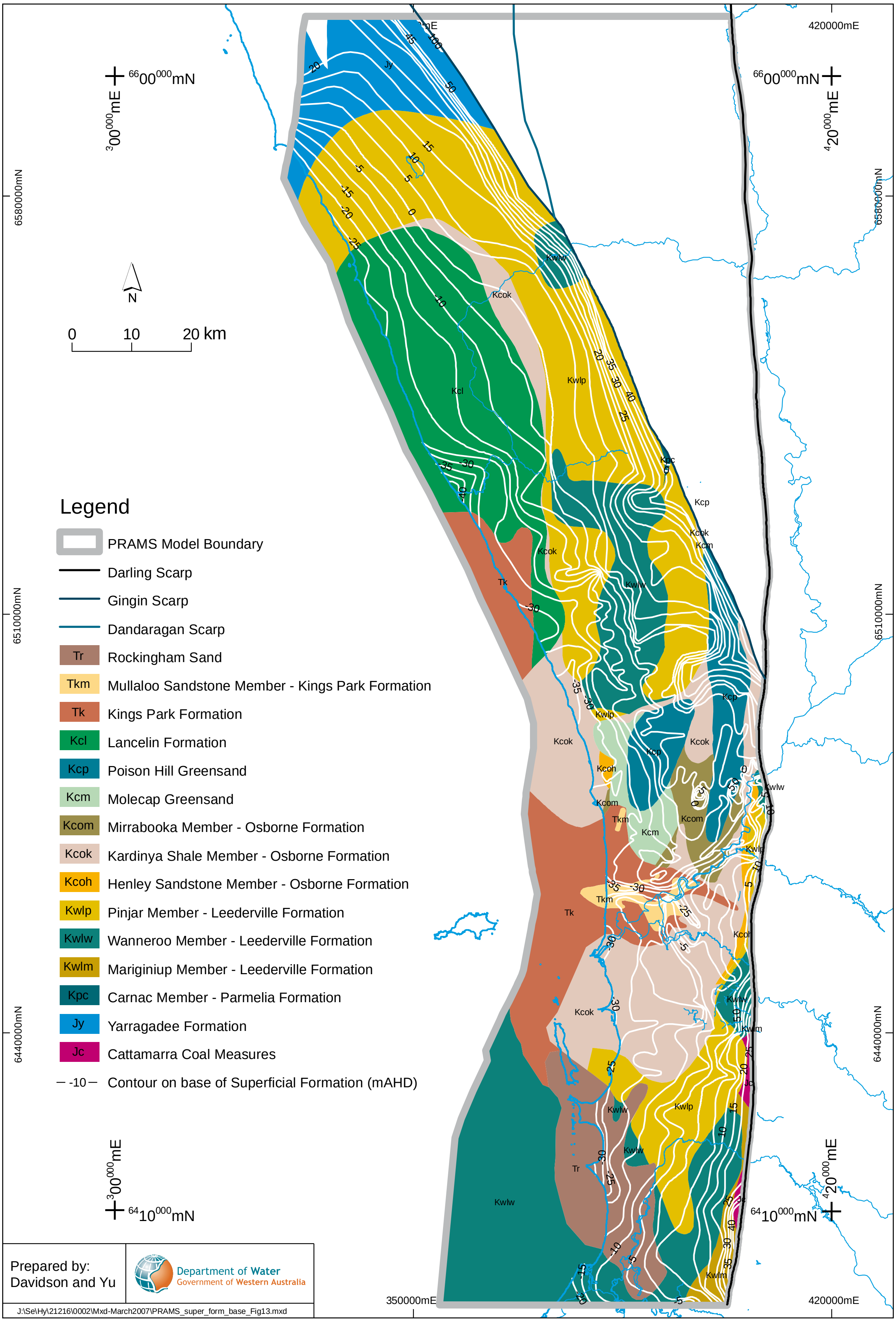


Figure 13 Superficial formations: contours on base of unit; with strata subcrop

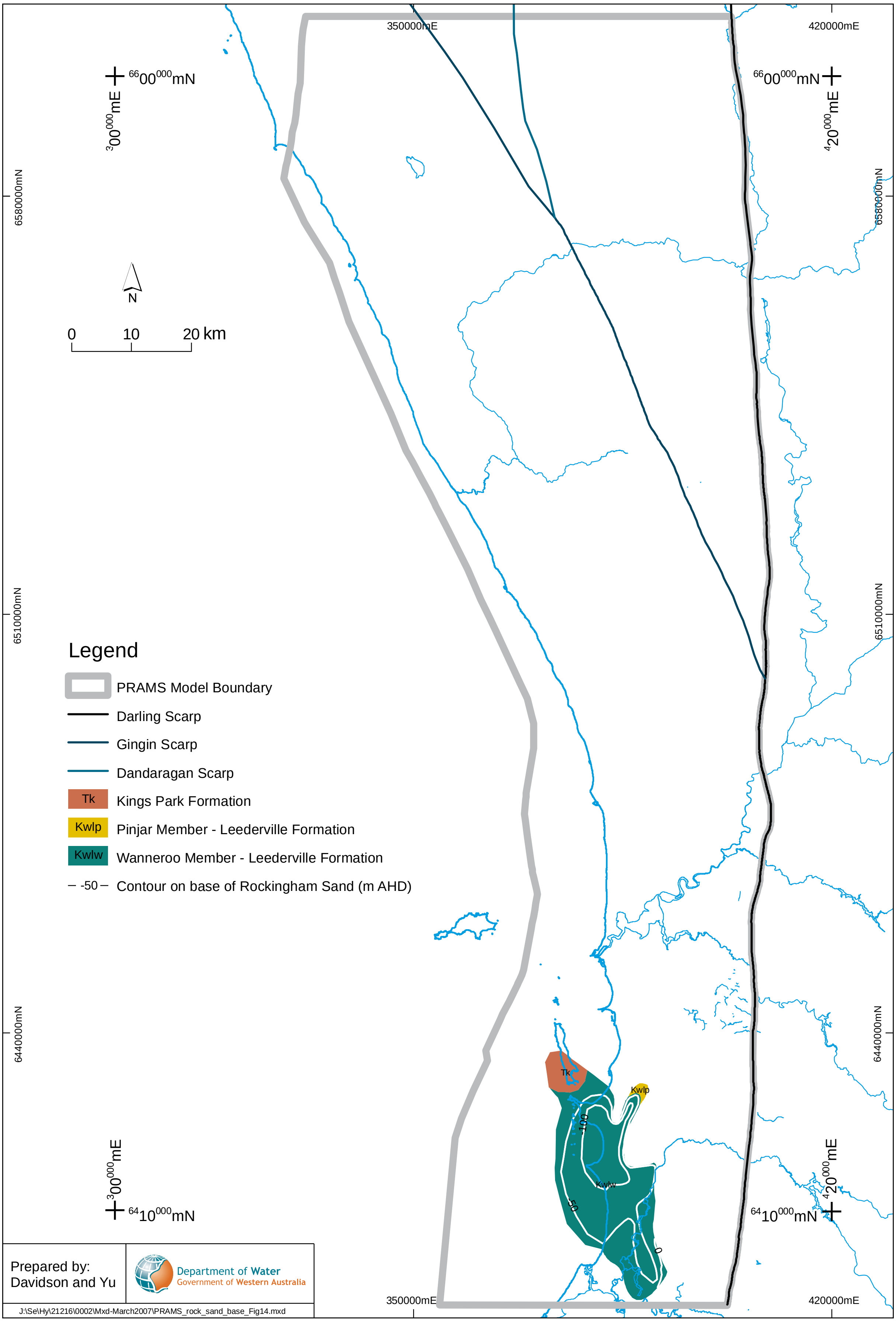


Figure 14 Rockingham Sand: contours on base of unit; with strata subcrop

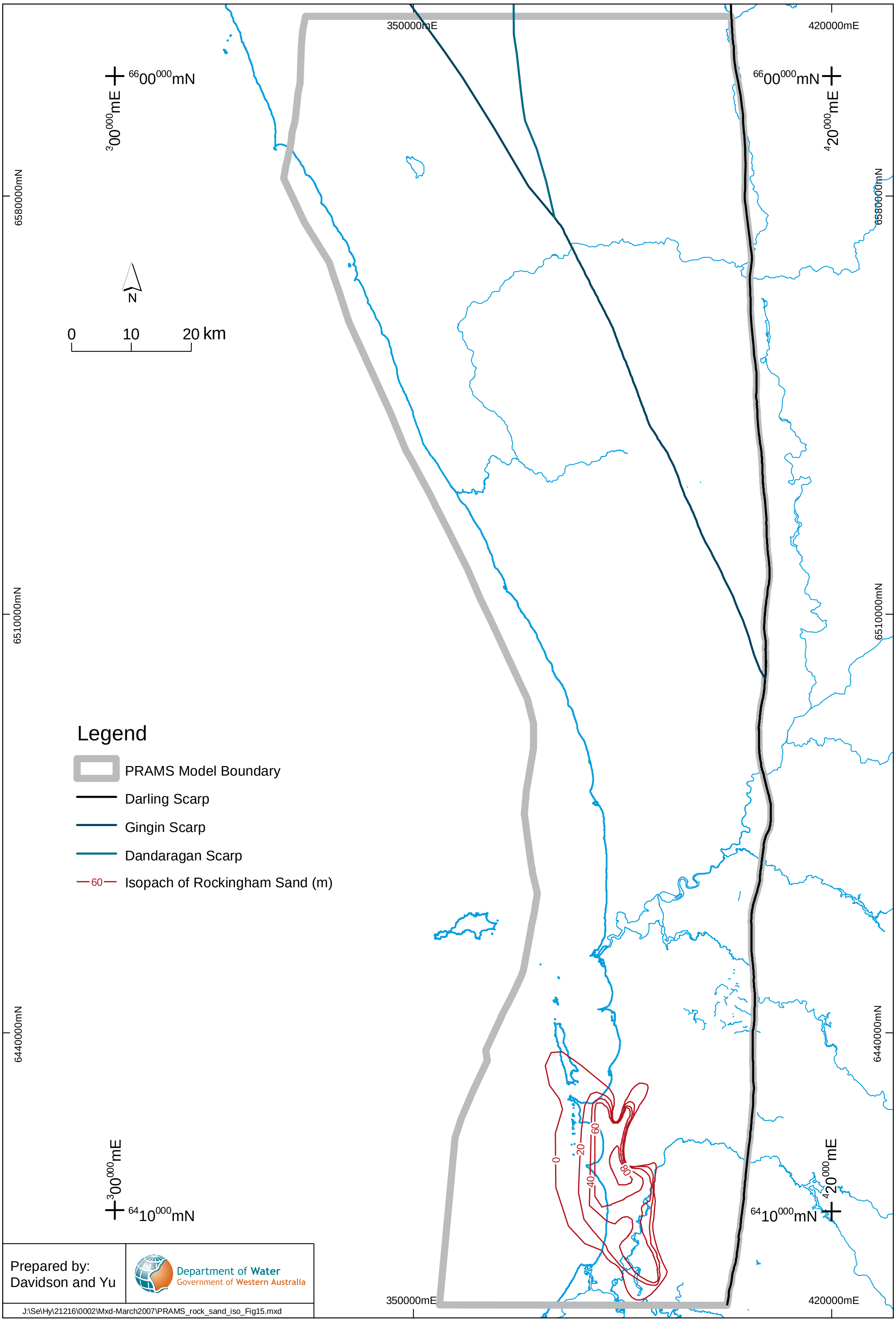


Figure 15 Rockingham Sand: isopachs

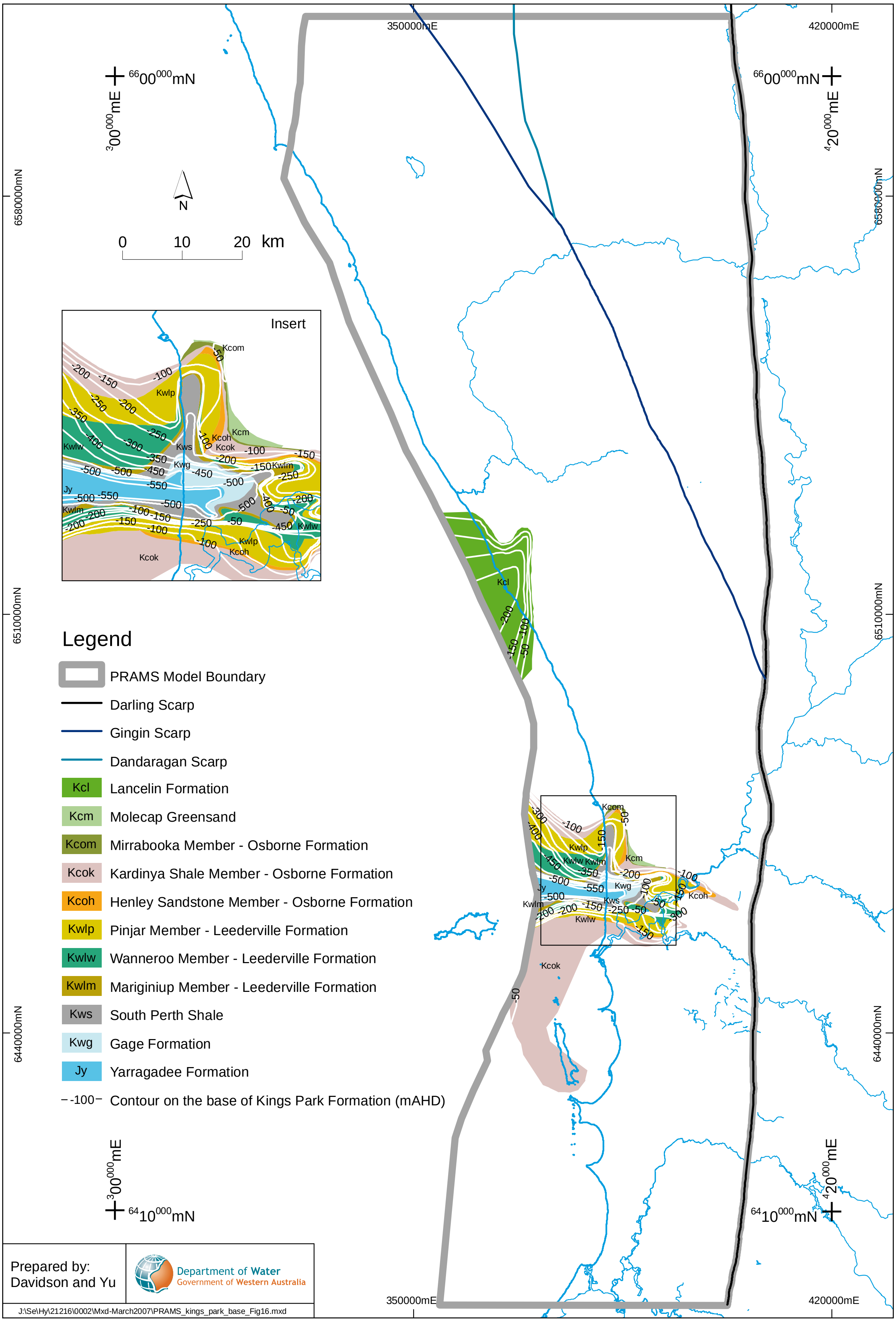


Figure 16 Kings Park Formation: contours on base of unit; with strata subcrop

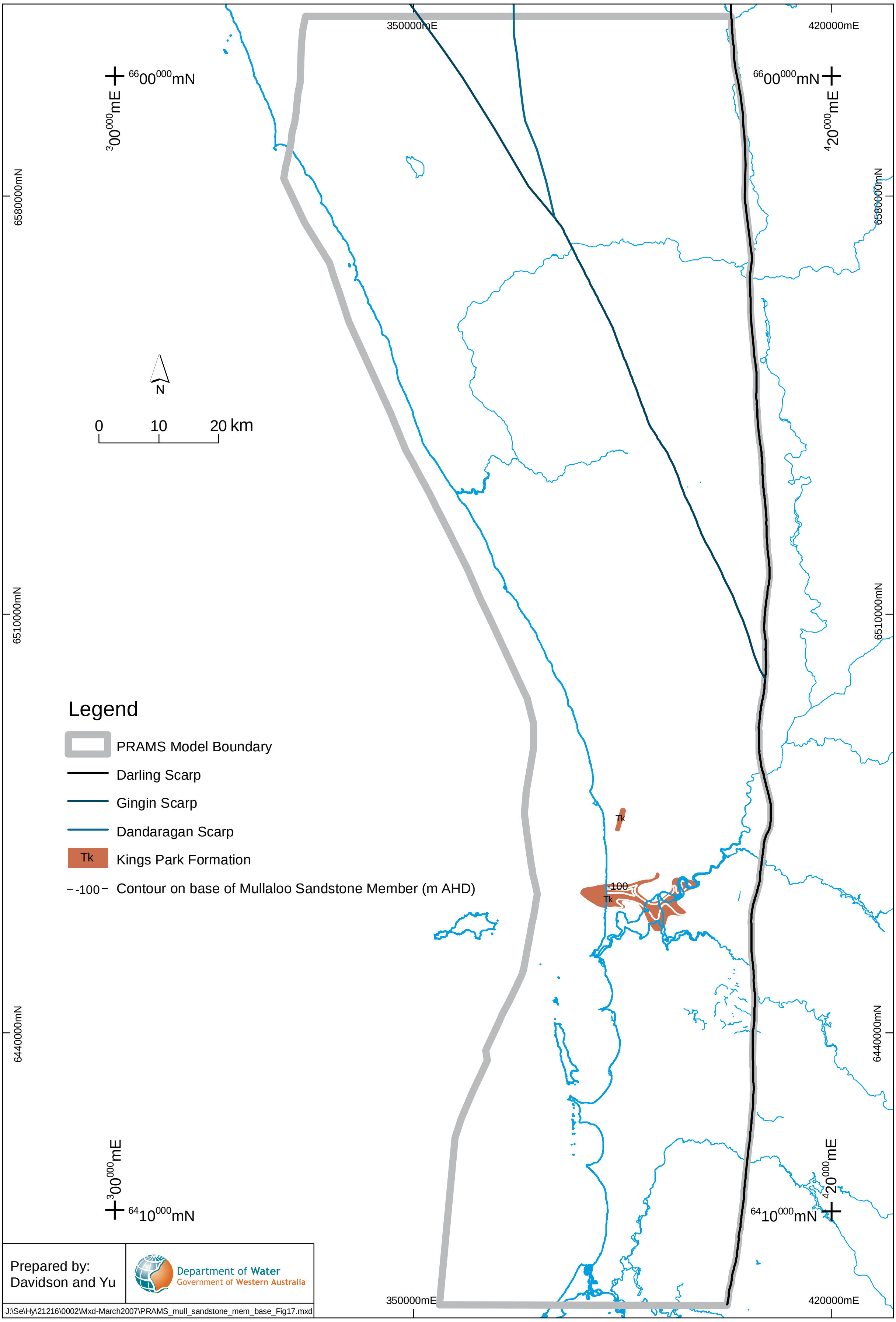


Figure 17 Mullaloo Sandstone Member: contours on base of unit; with strata subcrop

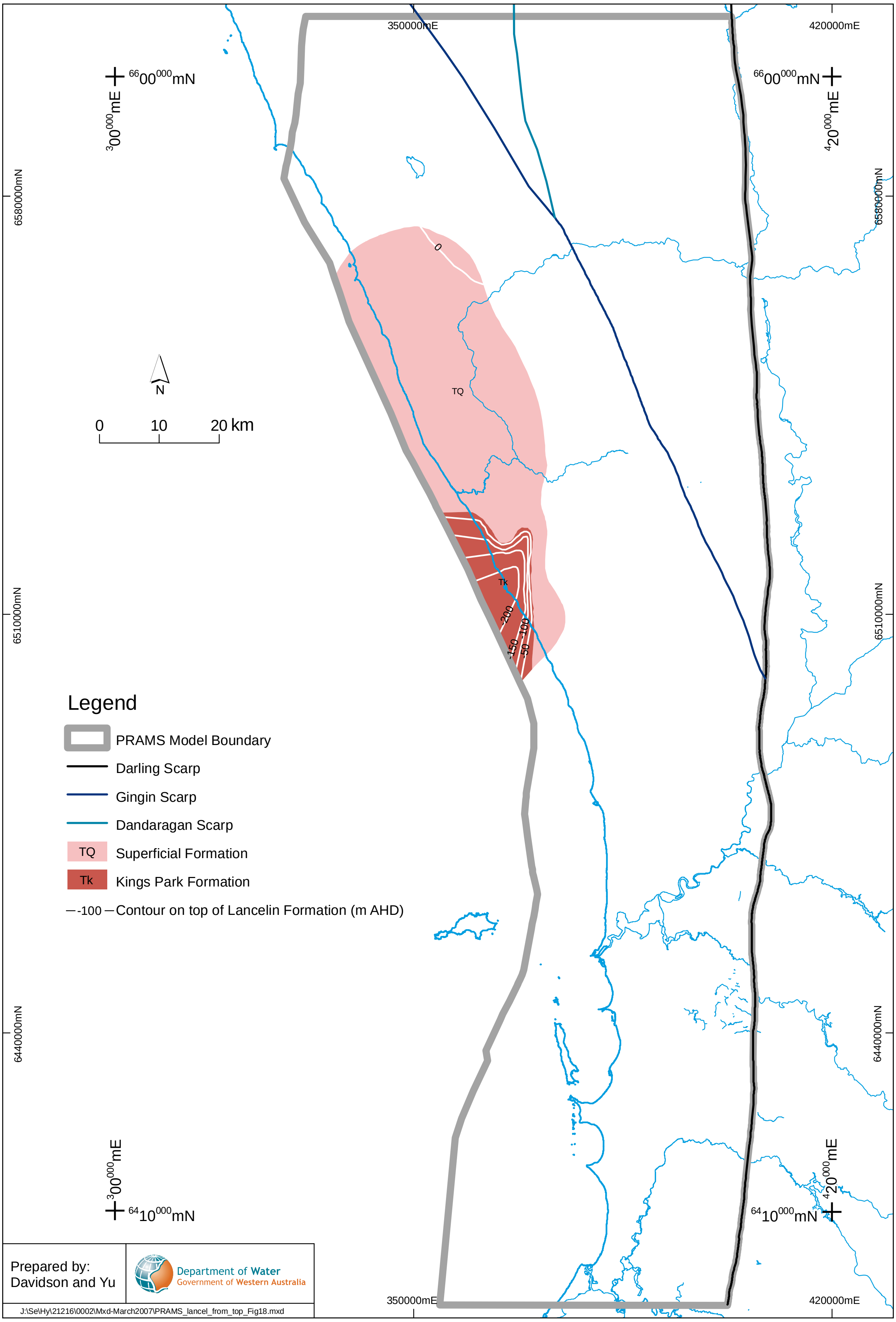


Figure 18 Lancelin Formation: contours on top of unit; with overlying strata

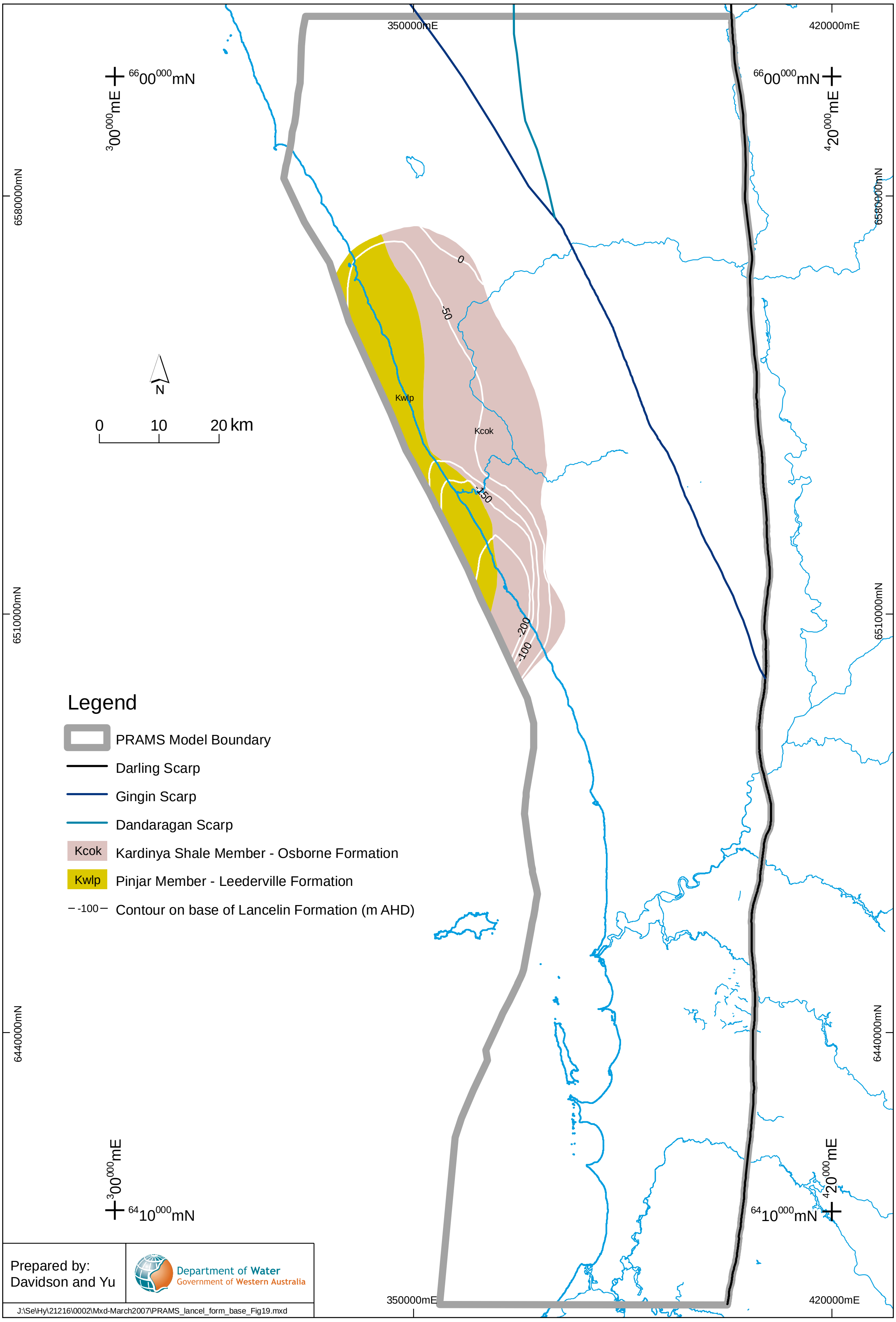


Figure 19 Lancelin Formation: contours on base of unit; with strata subcrop

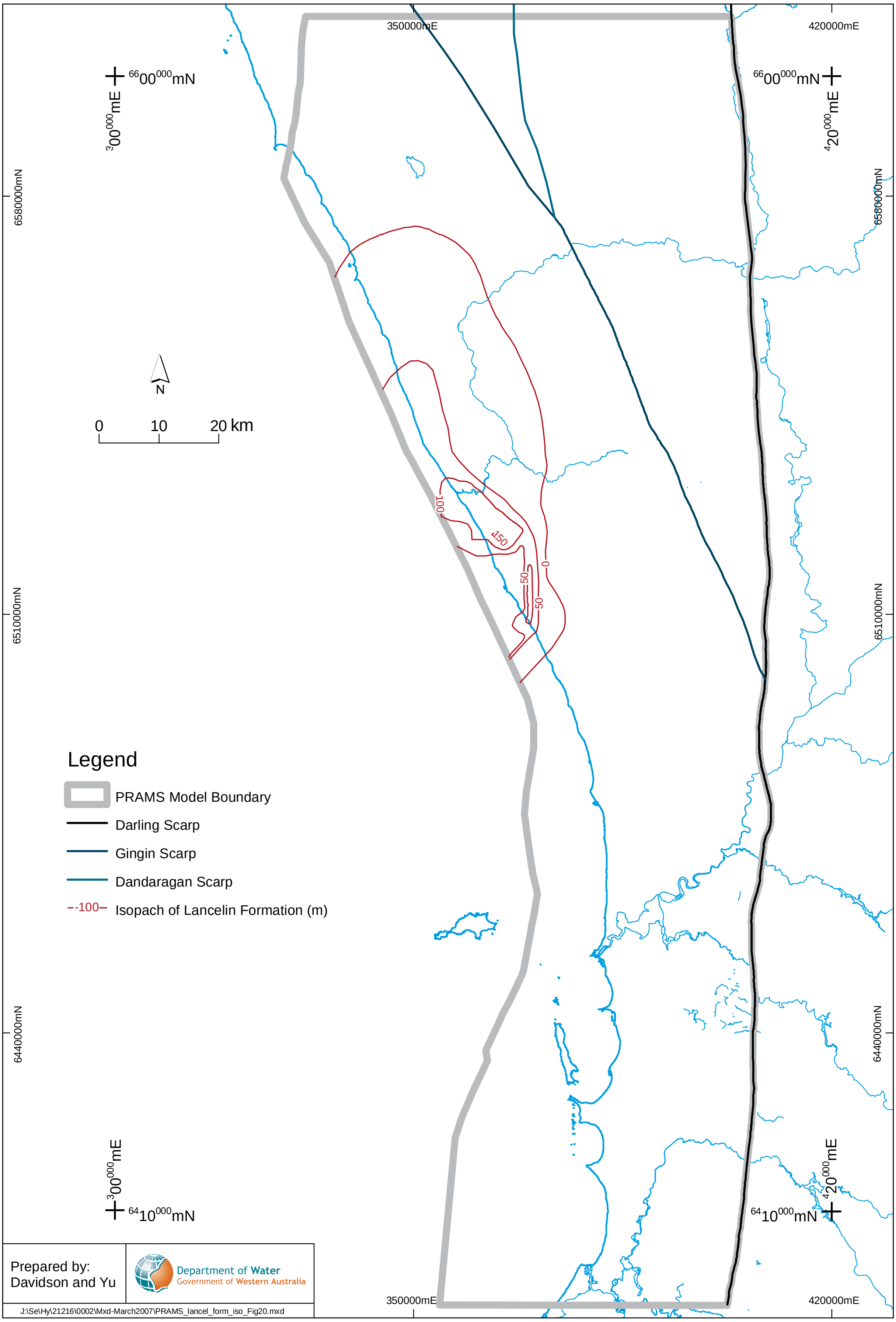


Figure 20 Lancelin Formation: isopachs

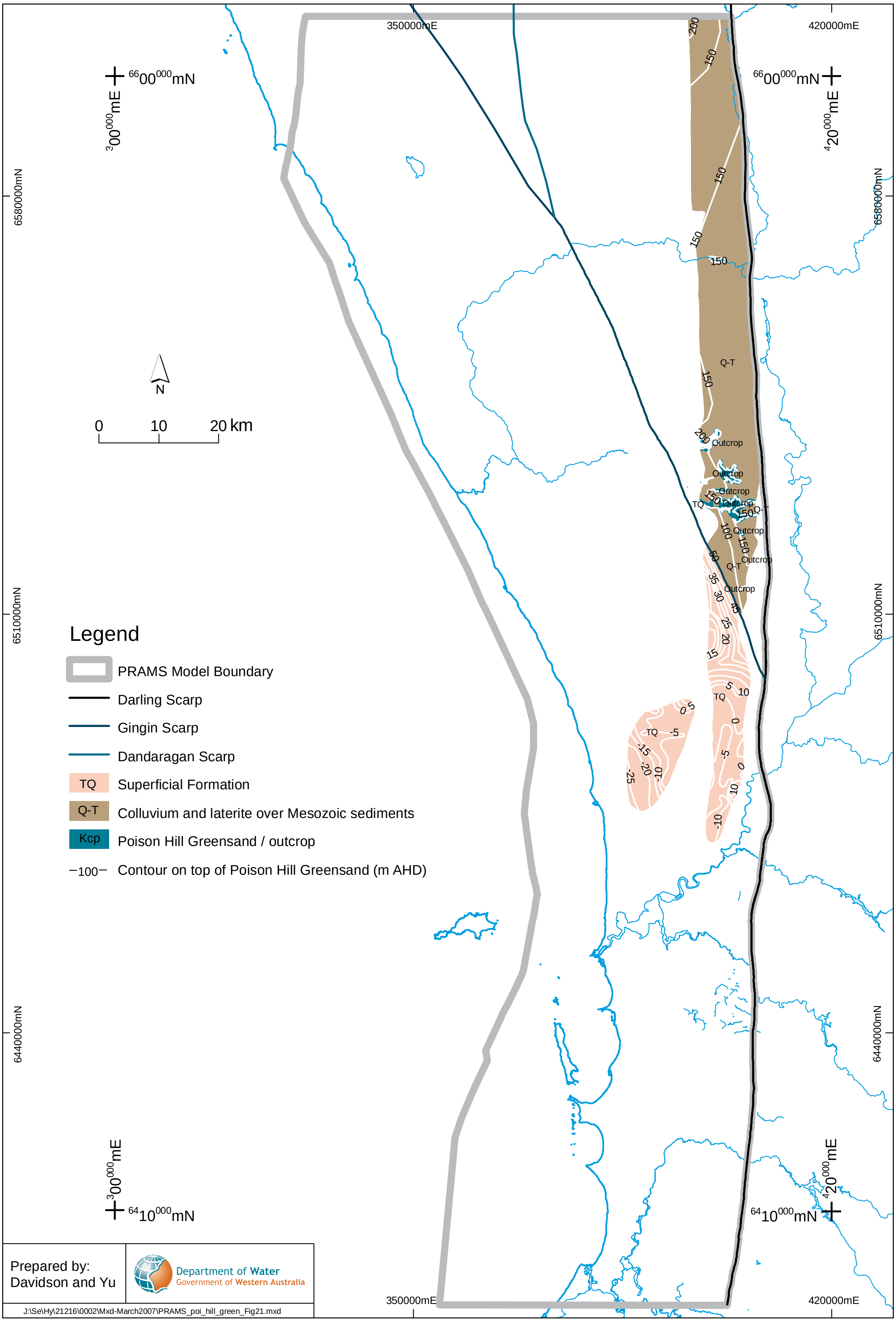


Figure 21 Poison Hill Greensand: contours on top of unit; with overlying strata

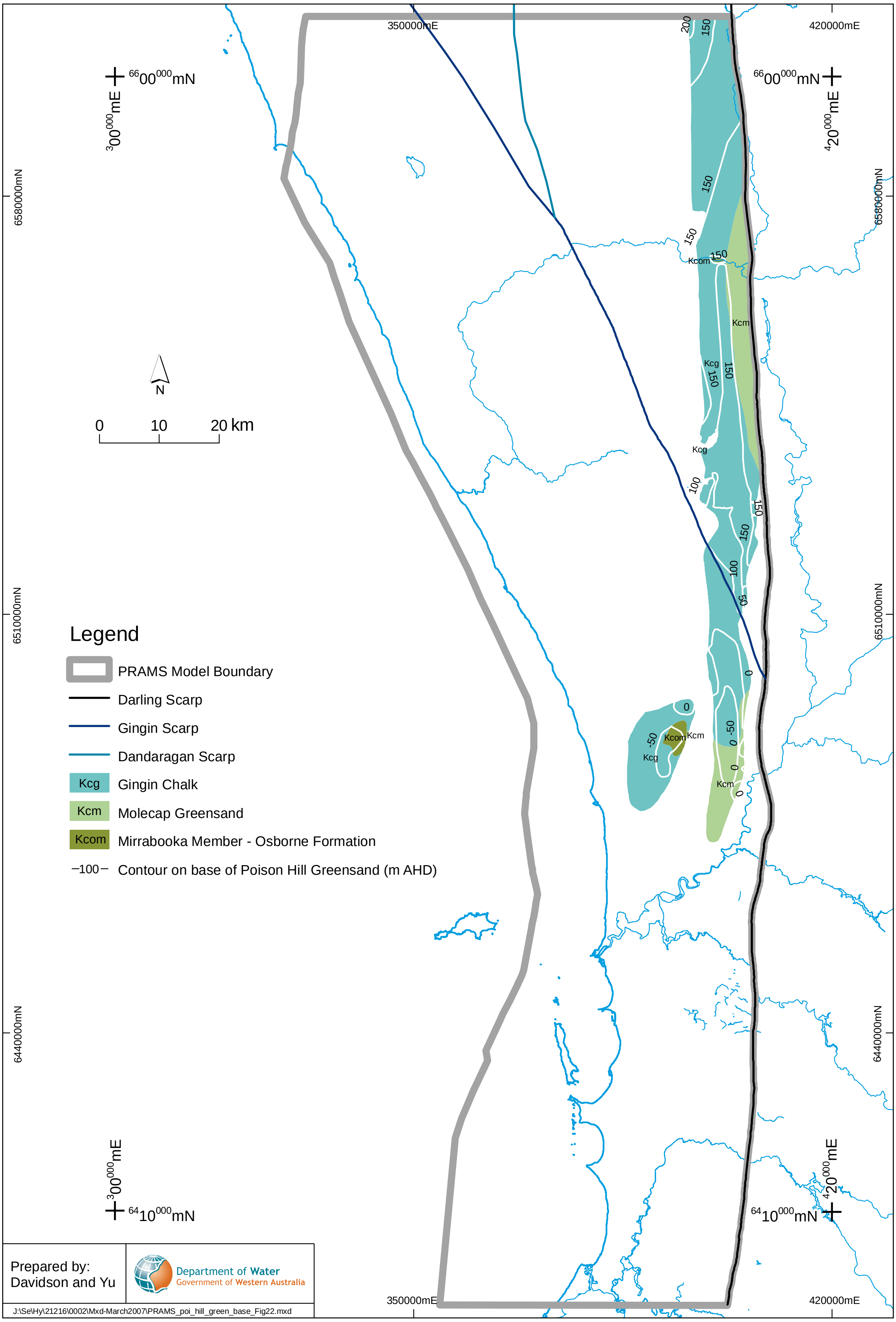


Figure 22 Poison Hill Greensand: contours on base of unit; with strata subcrop

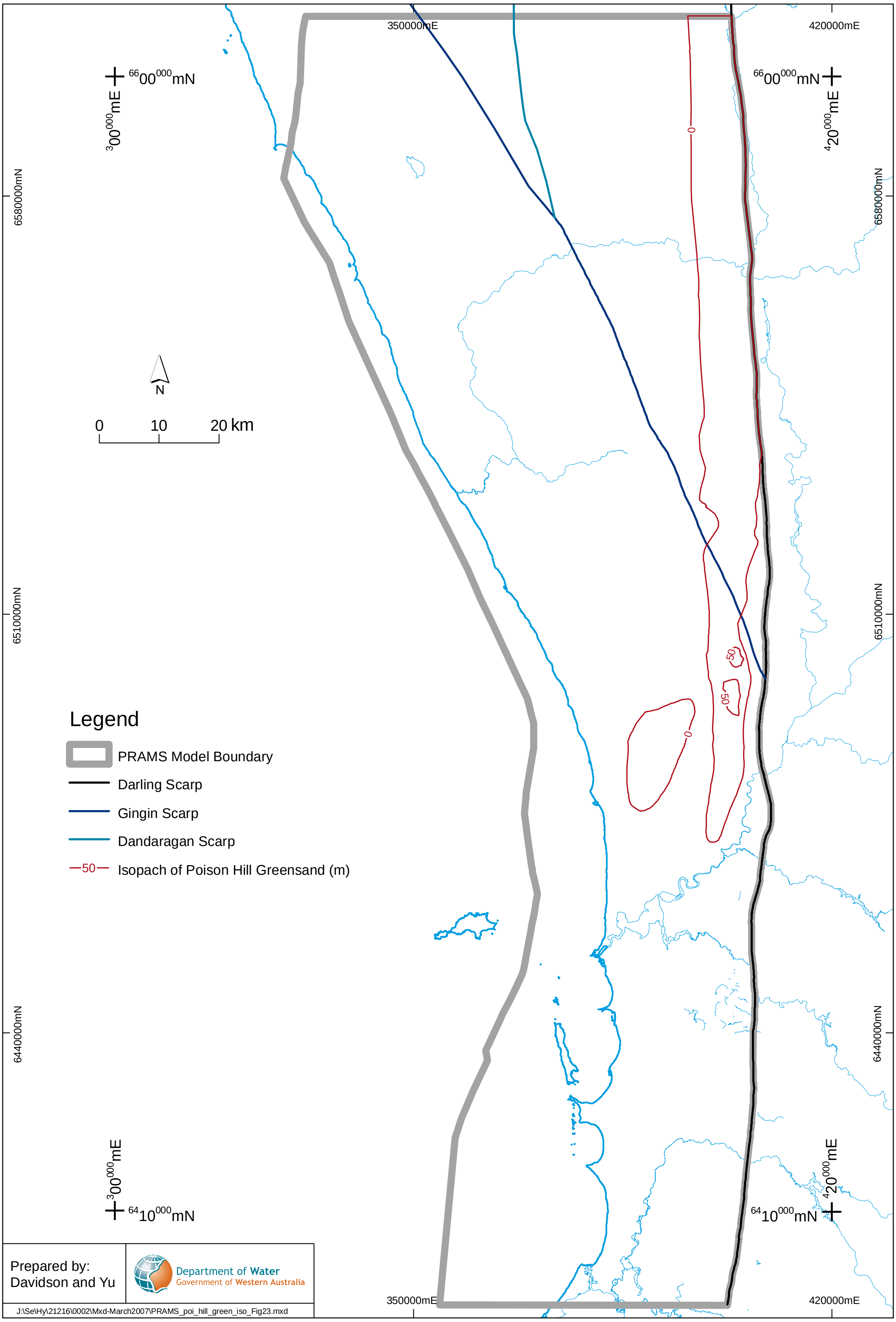


Figure 23 Poison Hill Greensand: isopachs

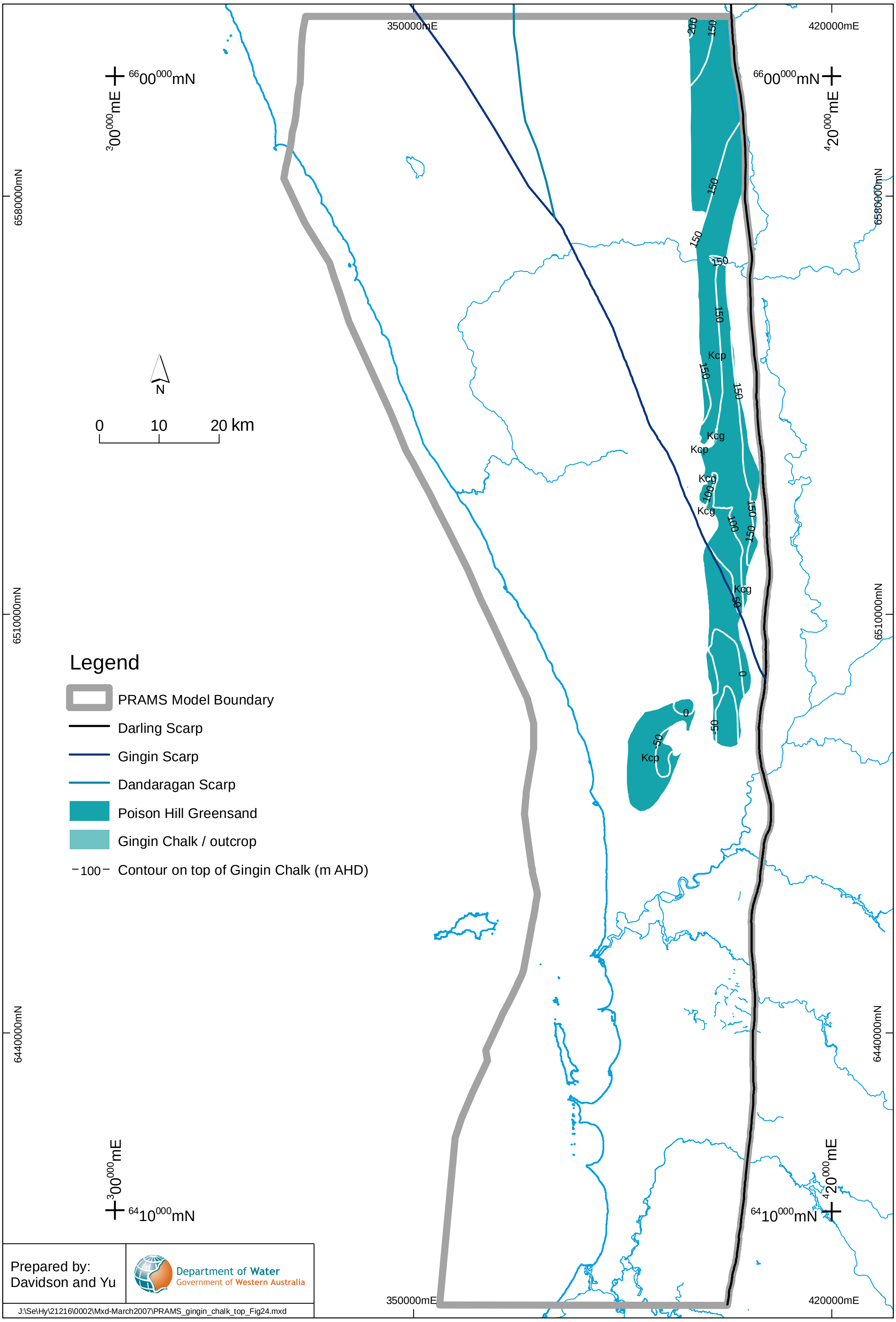


Figure 24 Gingin Chalk: contours on top of unit; with overlying strata

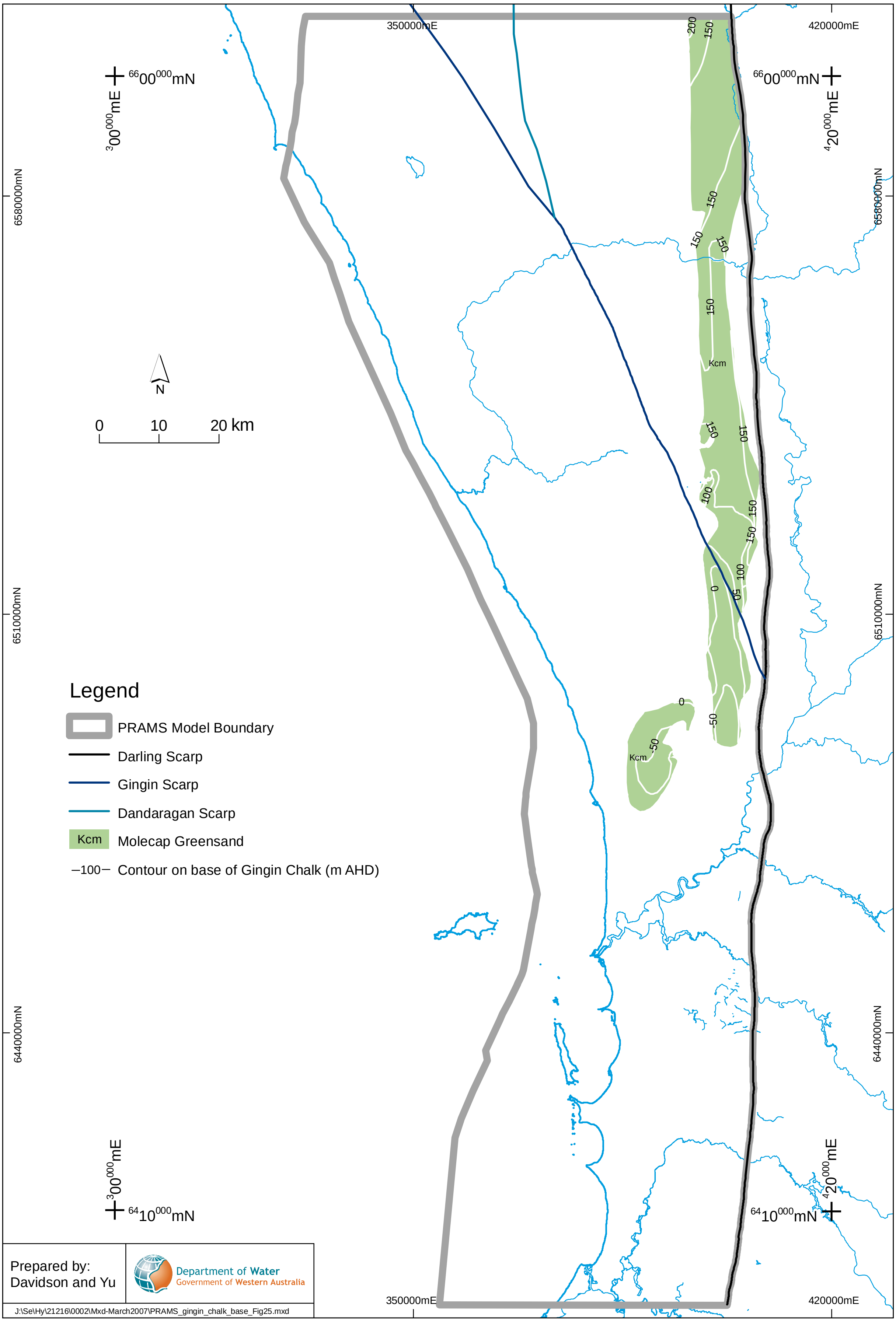


Figure 25 Gingin Chalk: contours on base of unit; with strata subcrop

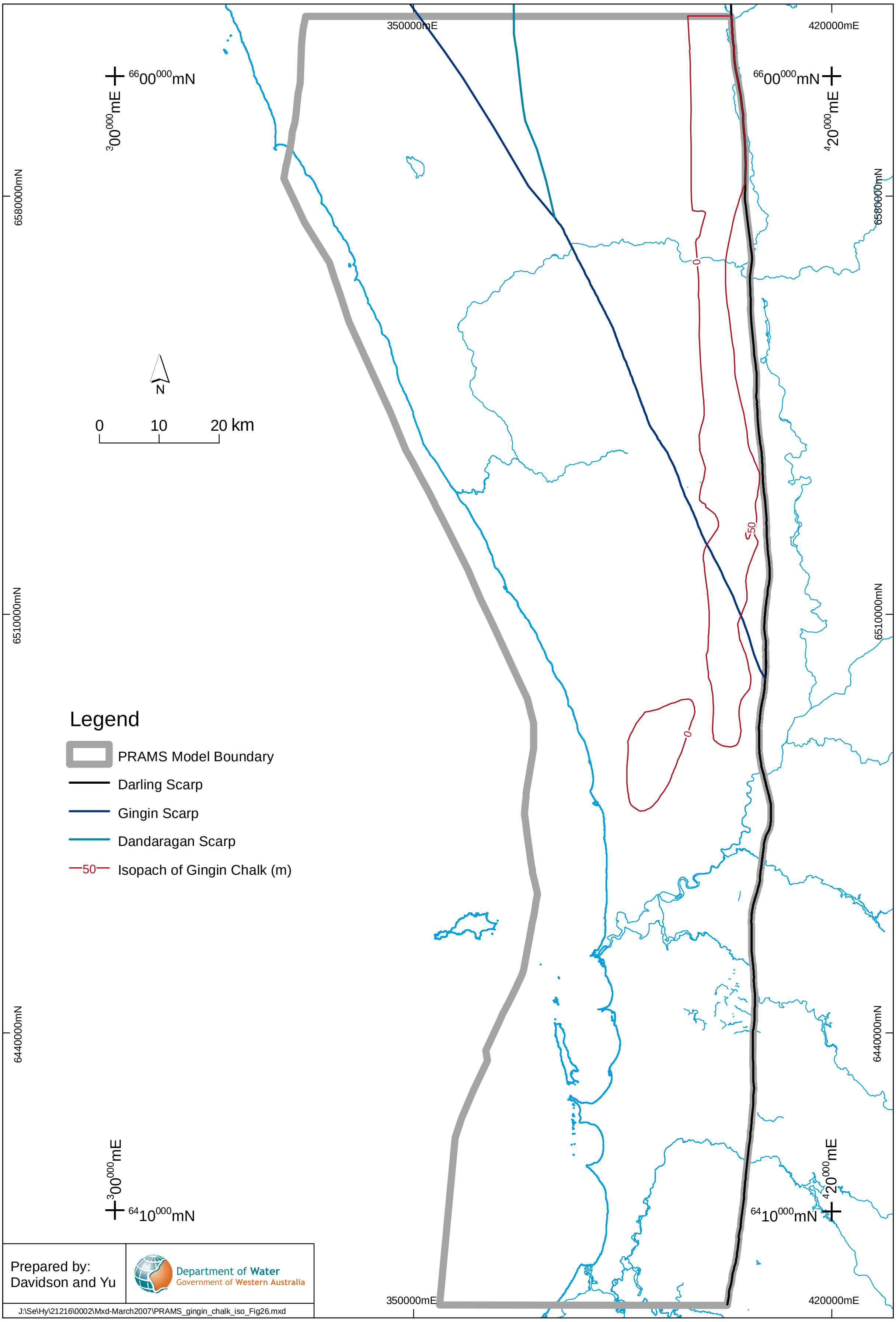


Figure 26 Gingin Chalk: isopachs

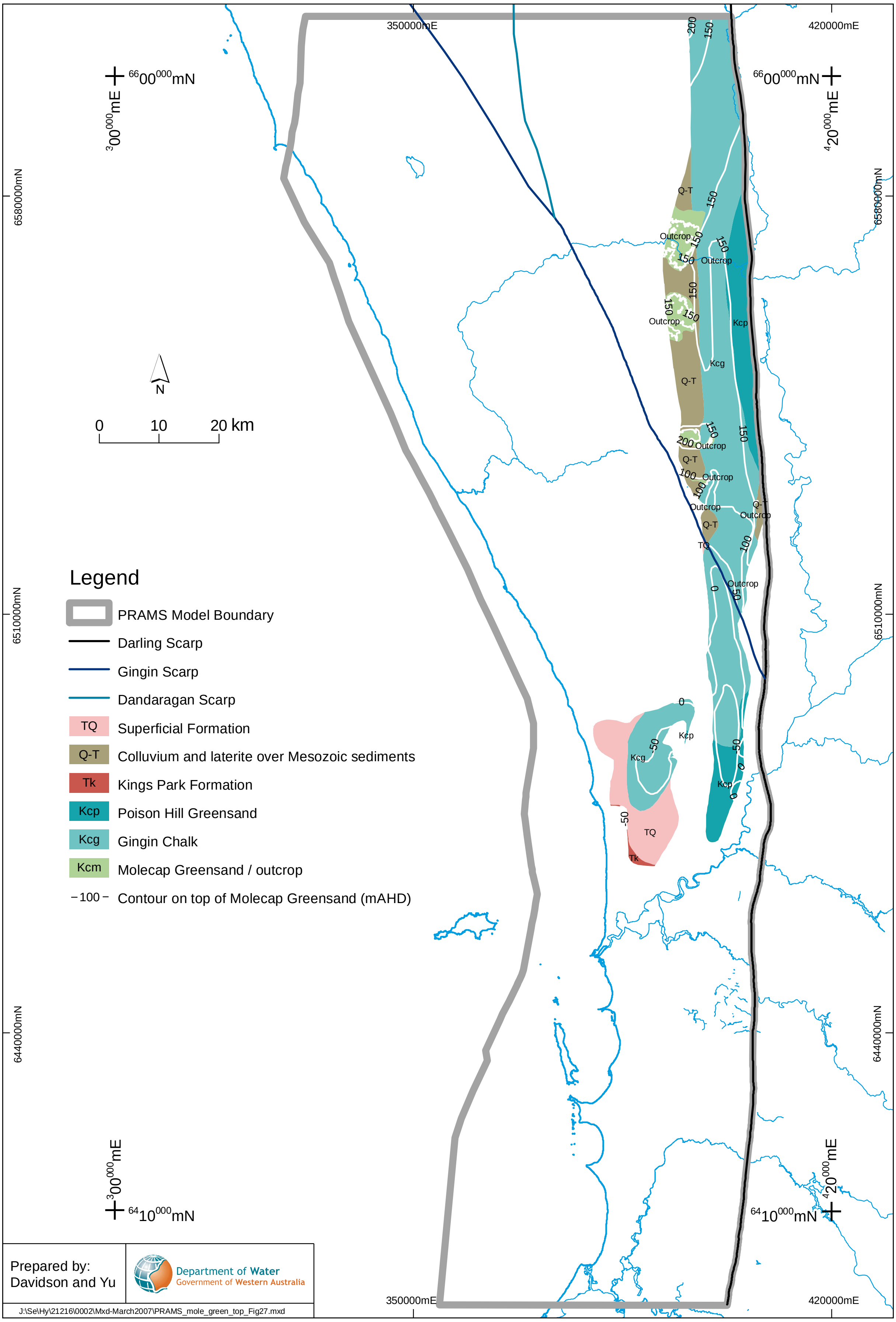


Figure 27 Molecap Greensand: contours on top of unit; with overlying strata

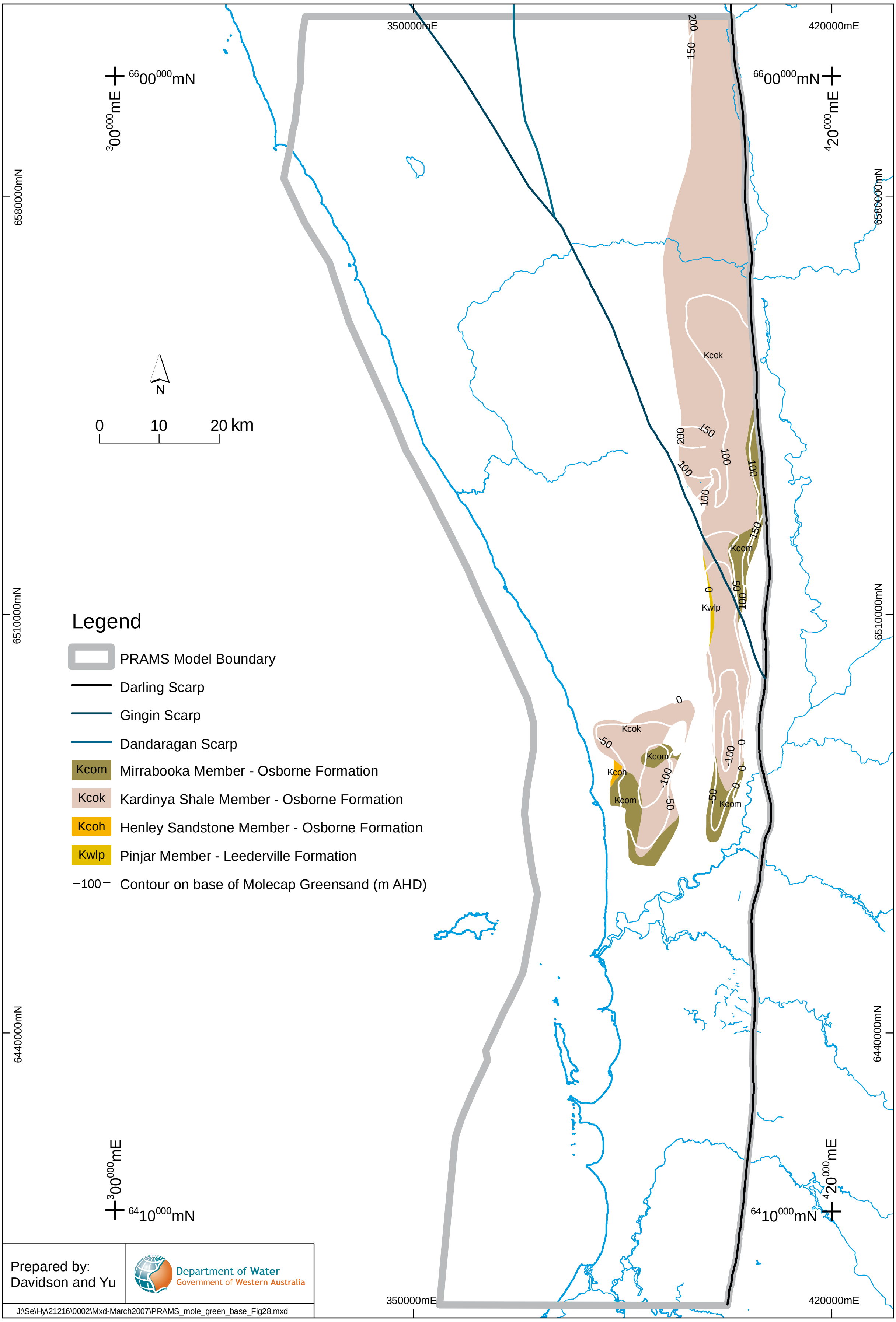


Figure 28 Molecap Greensand: contours on base of unit; with strata subcrop

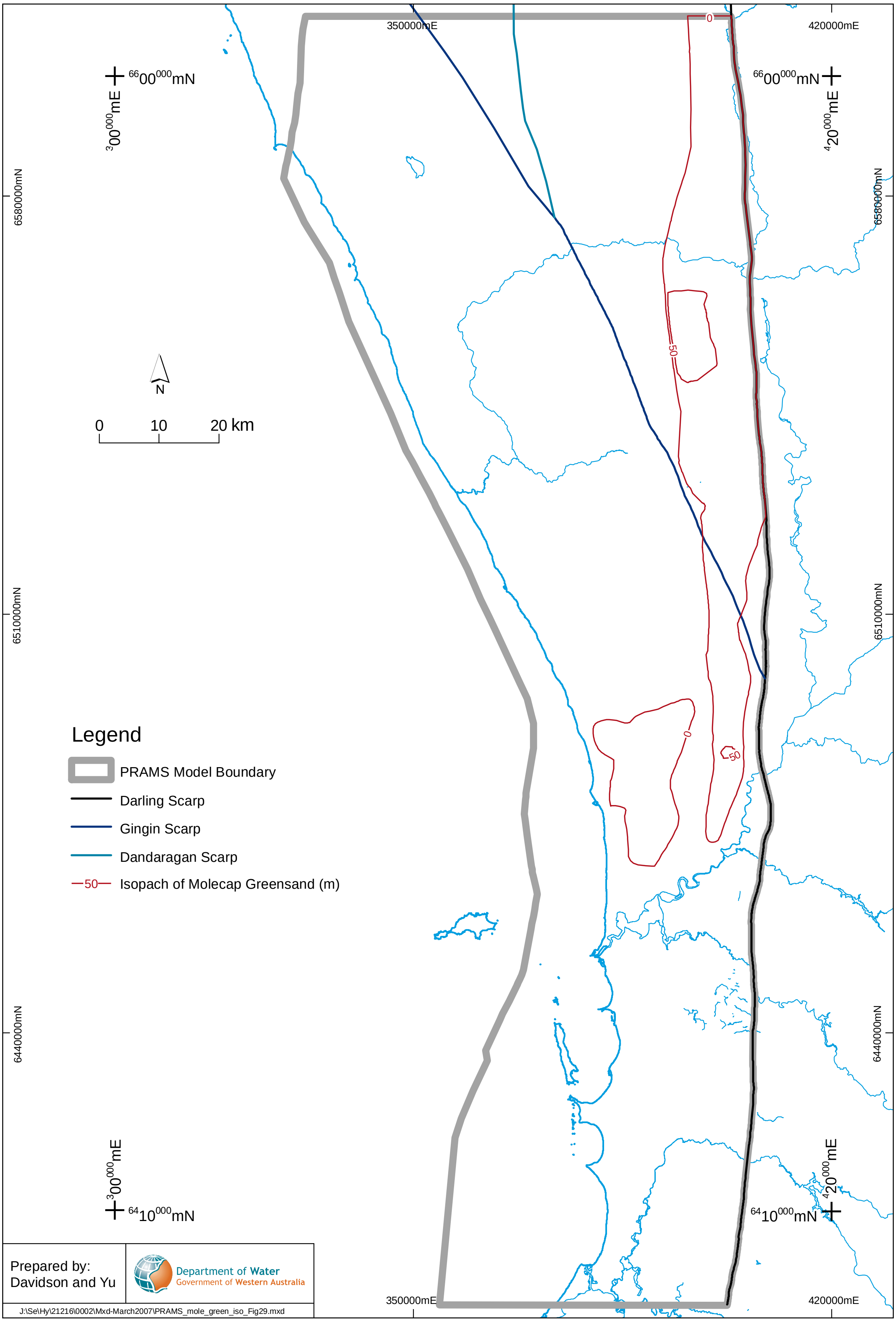


Figure 29 Molecap Greensand: isopachs

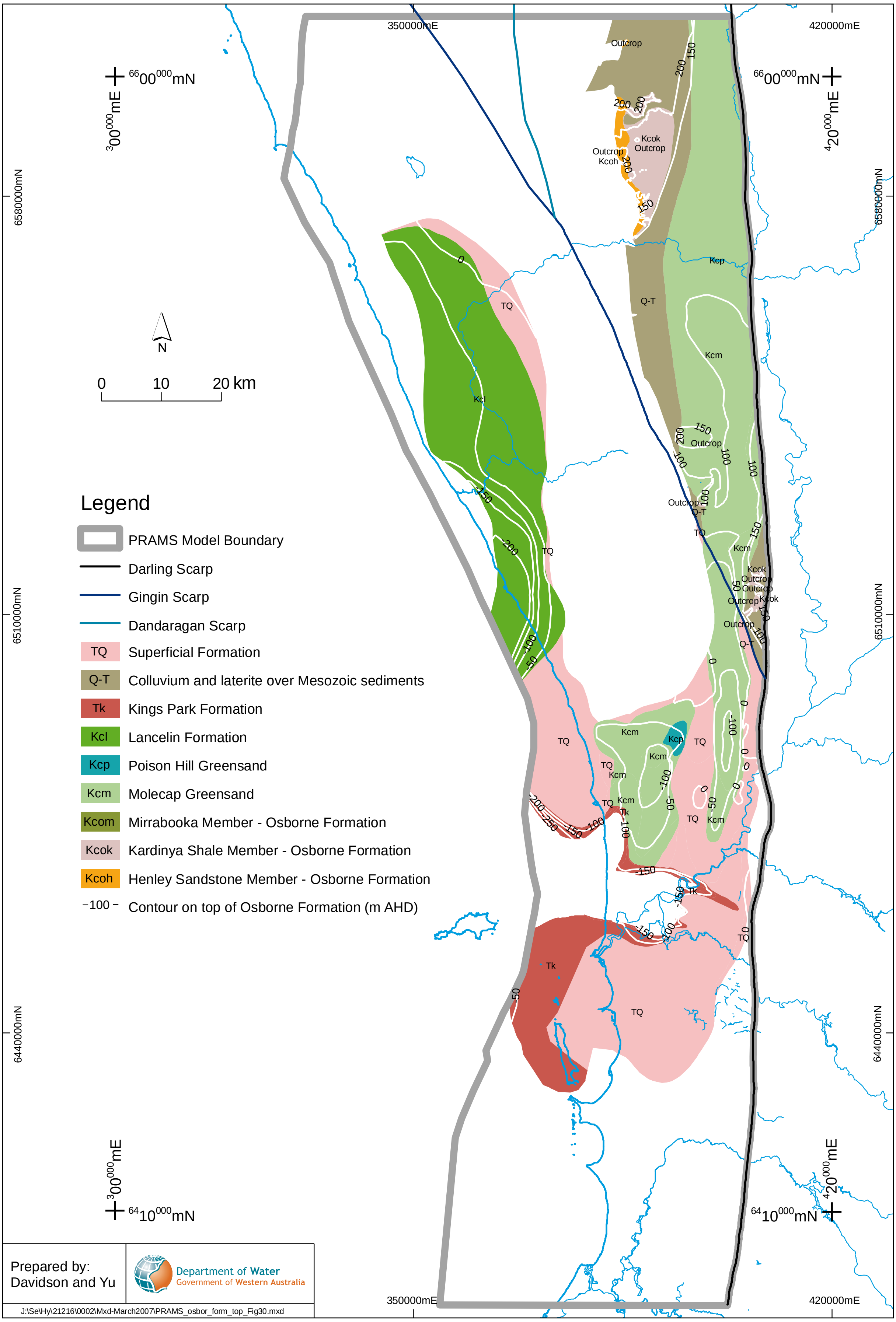


Figure 30 Osborne Formation: contours on top of unit; with overlying strata

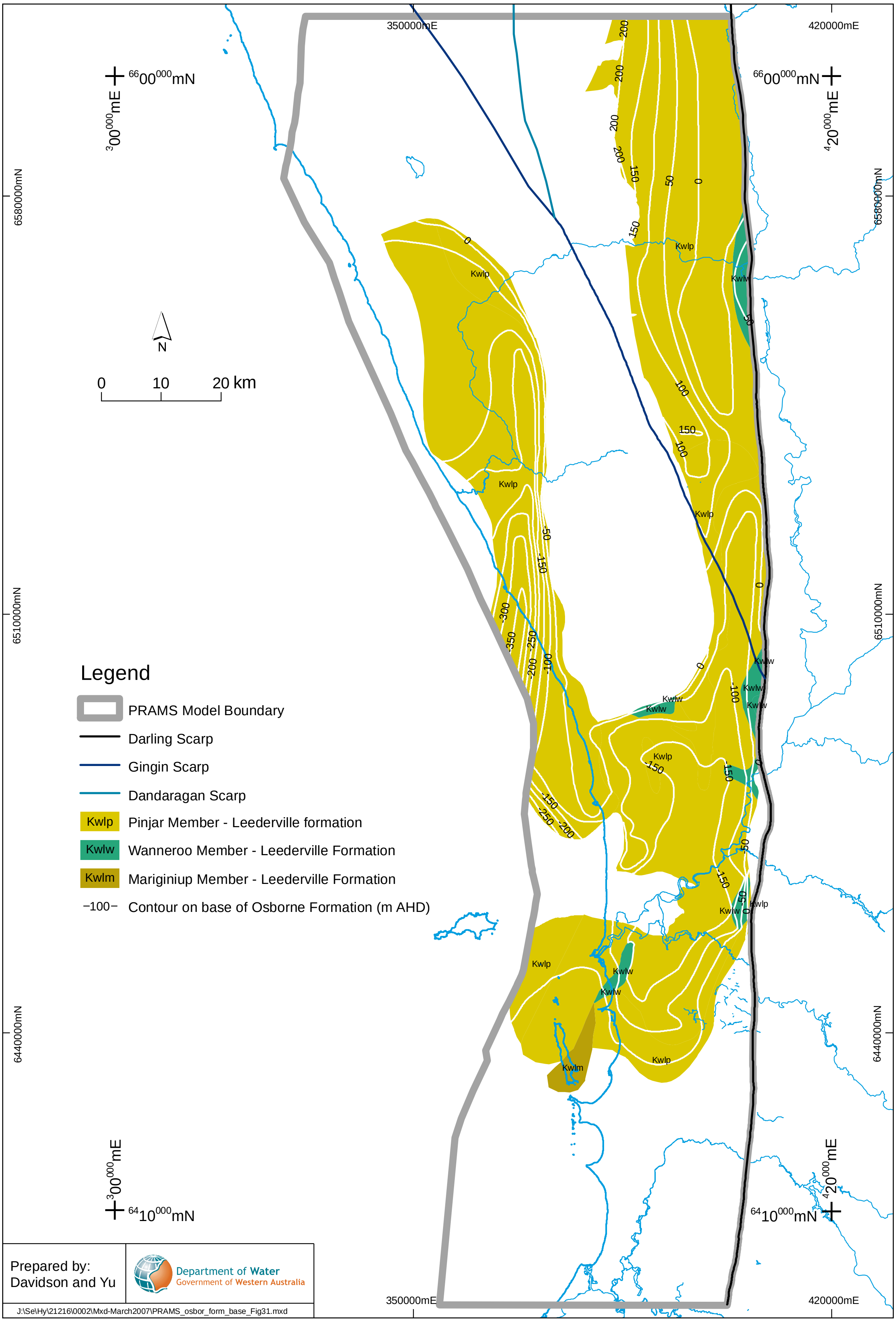


Figure 31 Osborne Formation: contours on base of unit; with strata subcrop

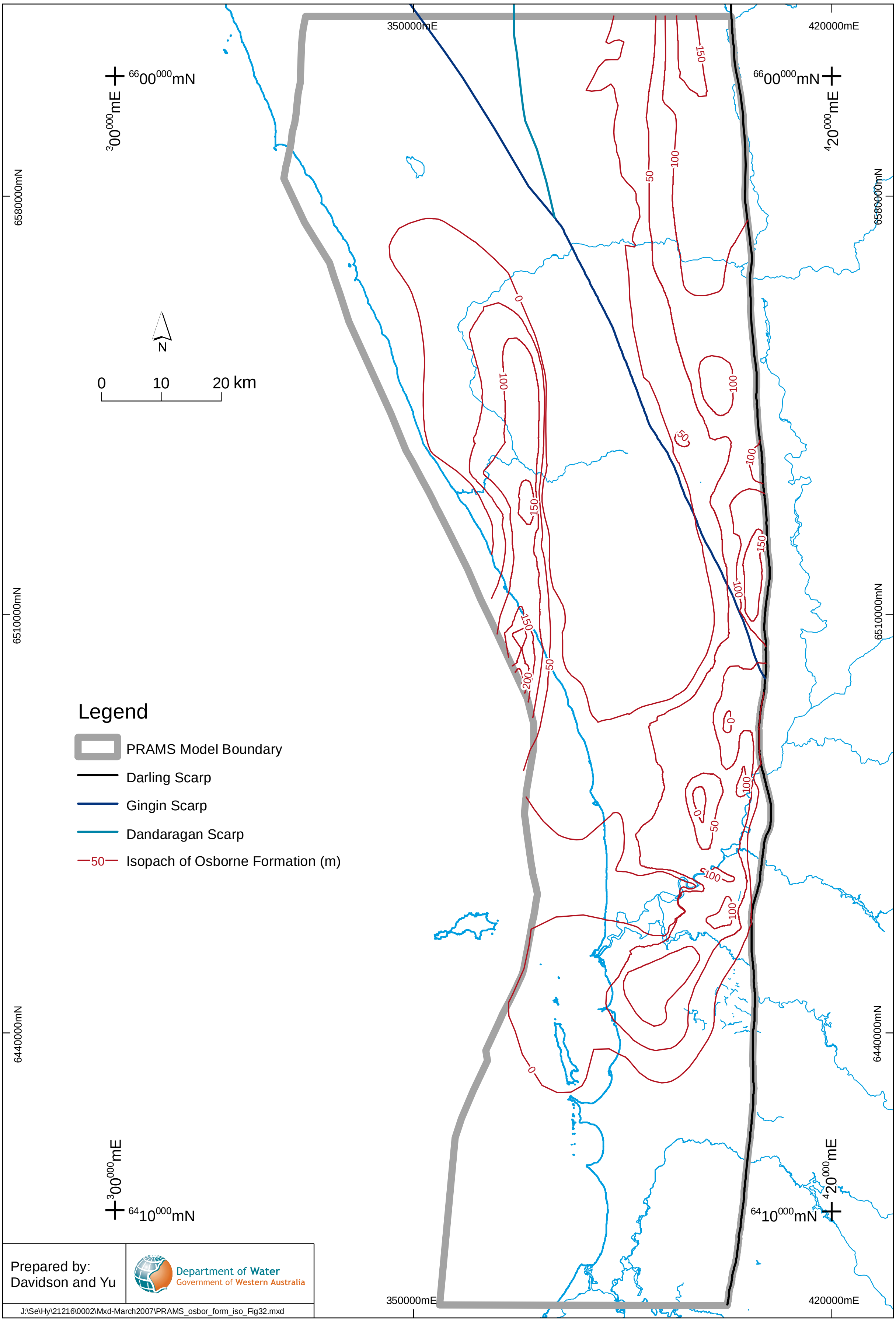


Figure 32 Osborne Formation: isopachs

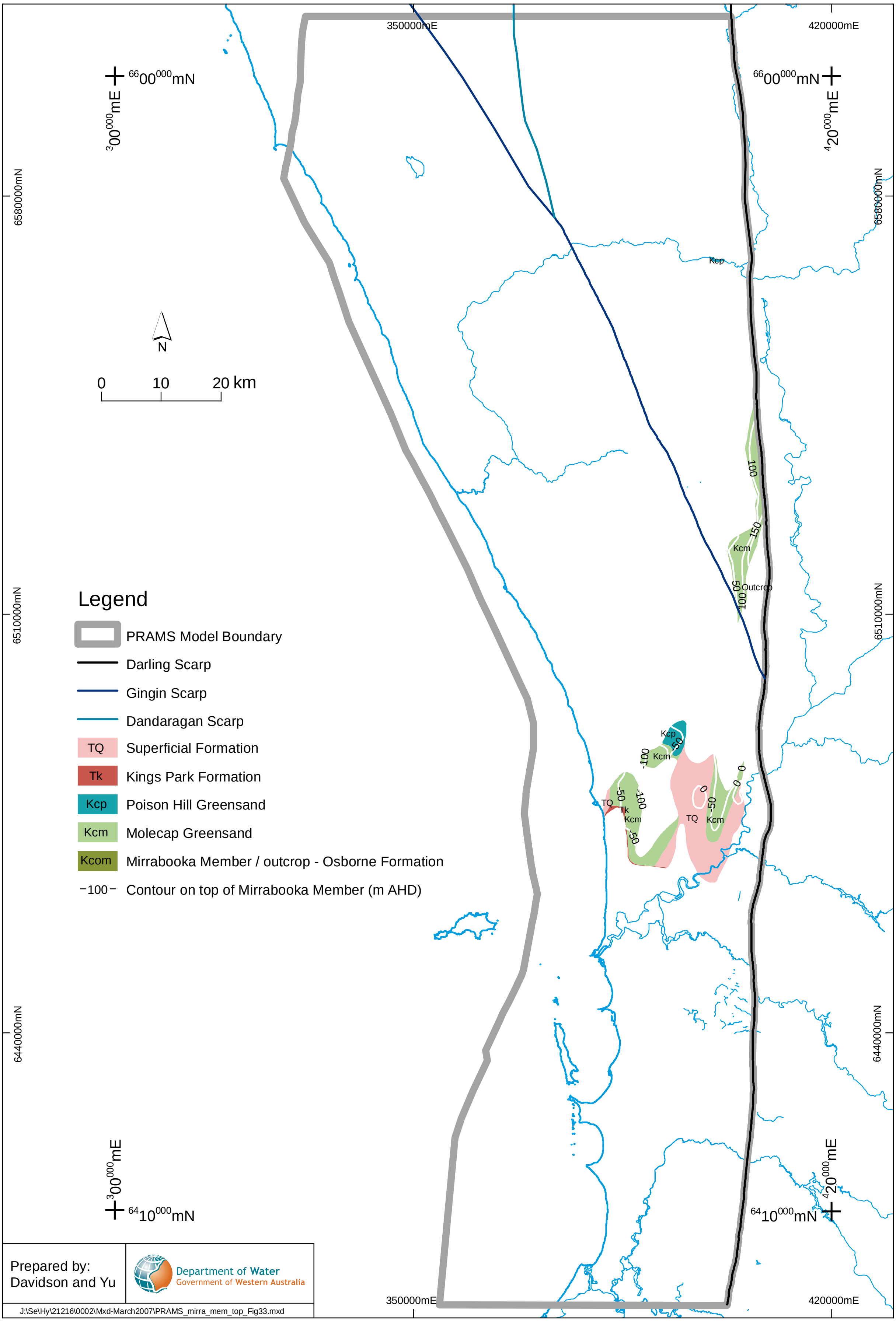


Figure 33 Mirrabooka Member: contours on top of unit; with overlying strata

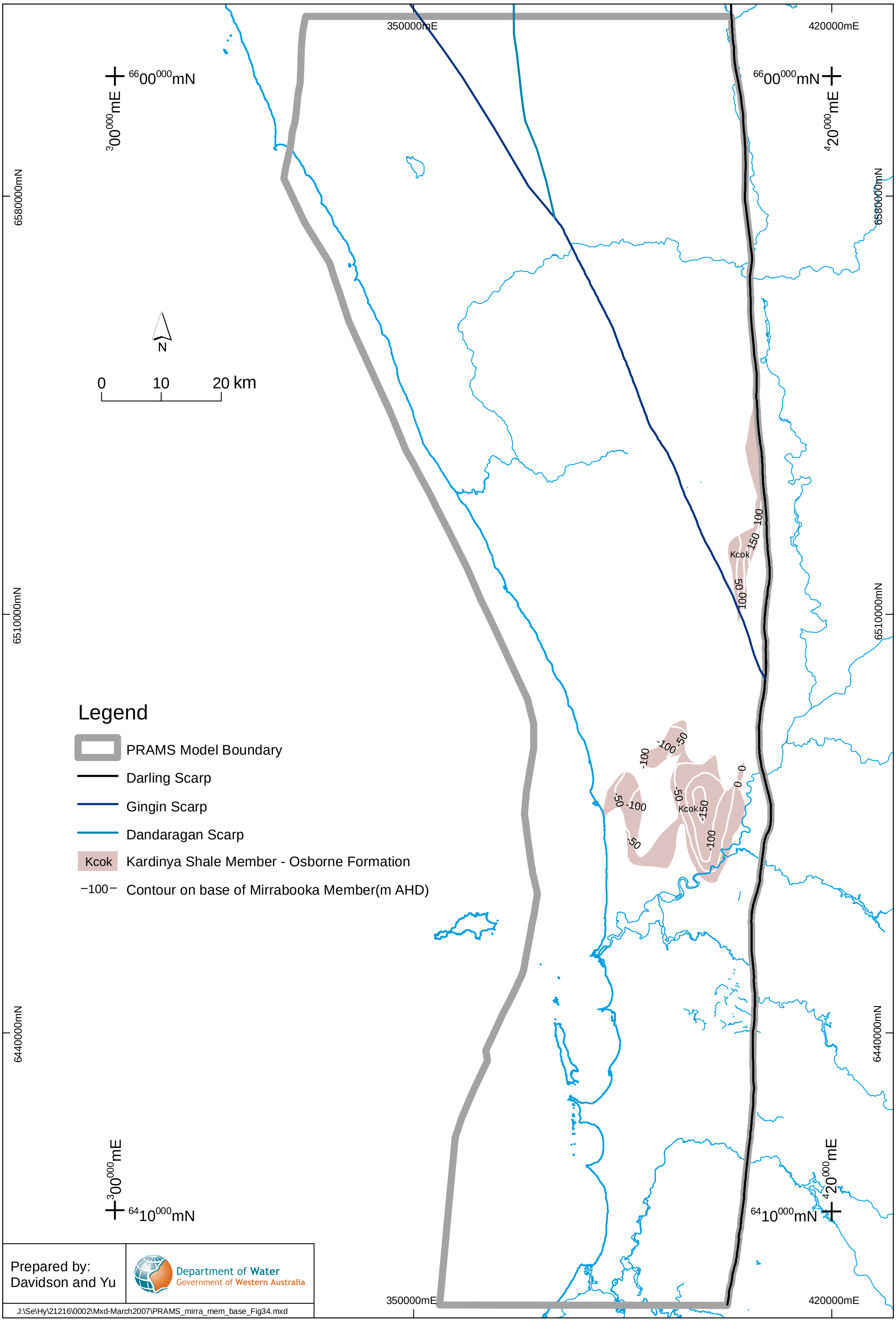


Figure 34 Mirrabooka Member: contours on base of unit; with strata subcrop

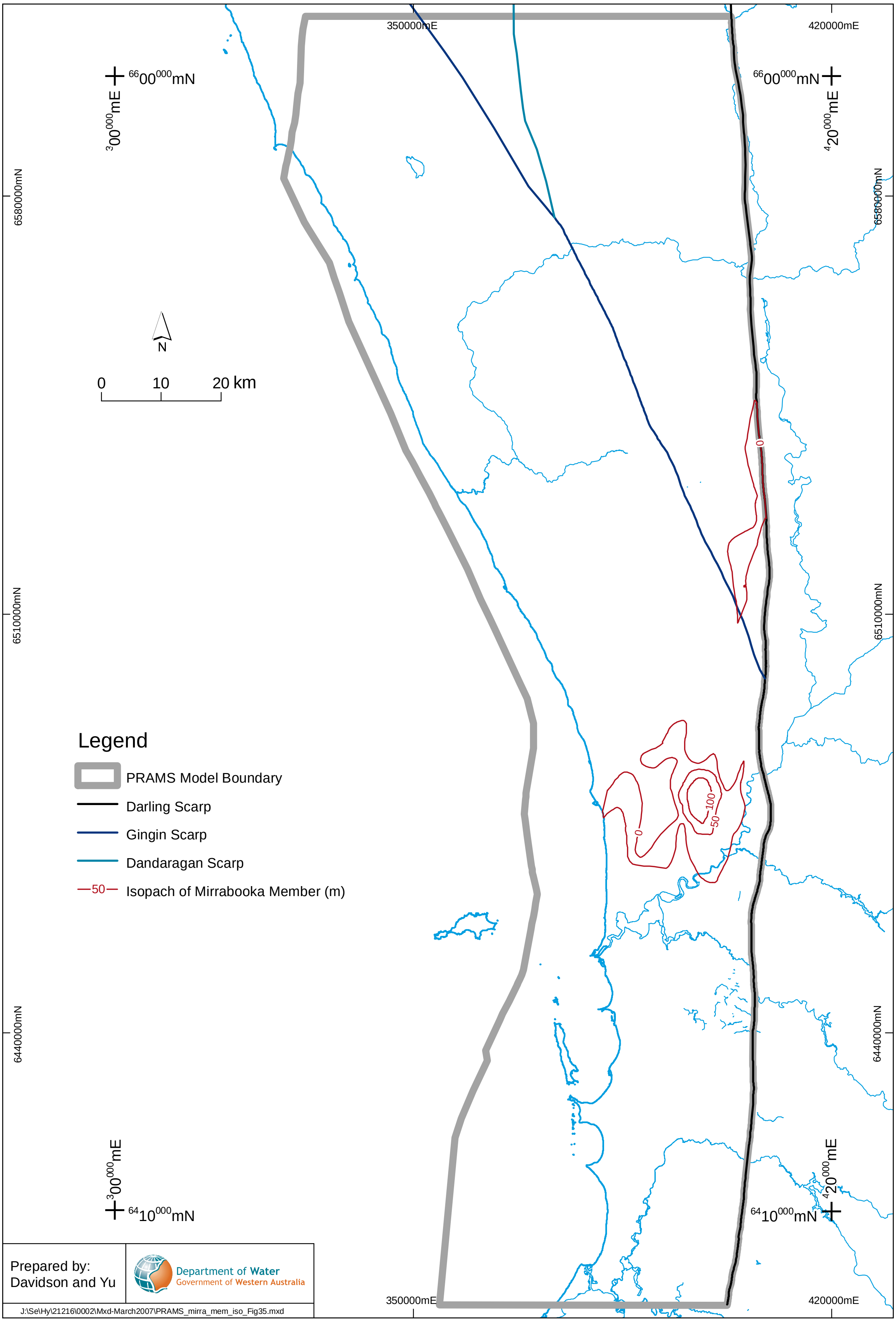


Figure 35 Mirrabooka Member: isopachs

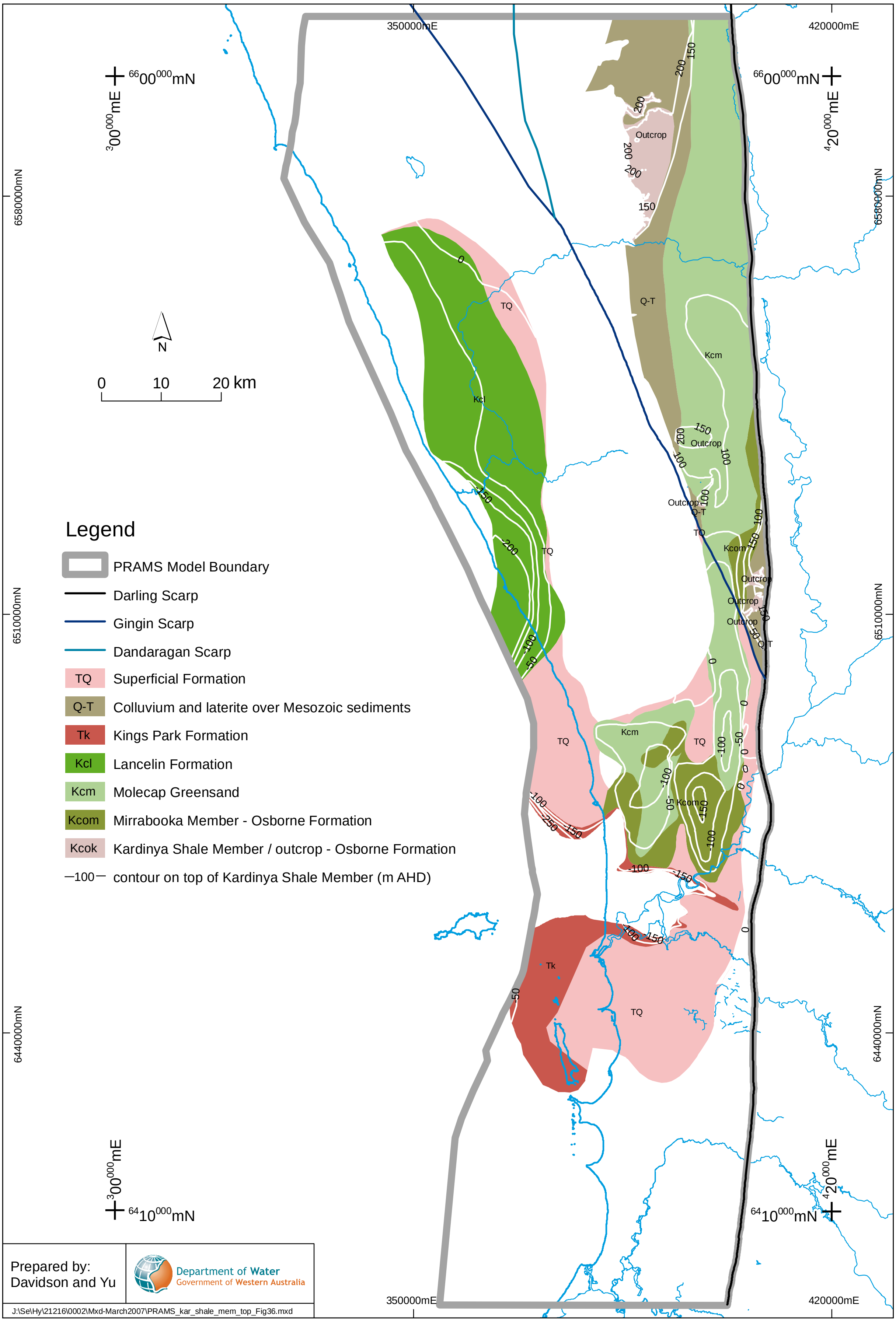


Figure 36 Kardinya Shale Member: contours on top of unit; with overlying strata

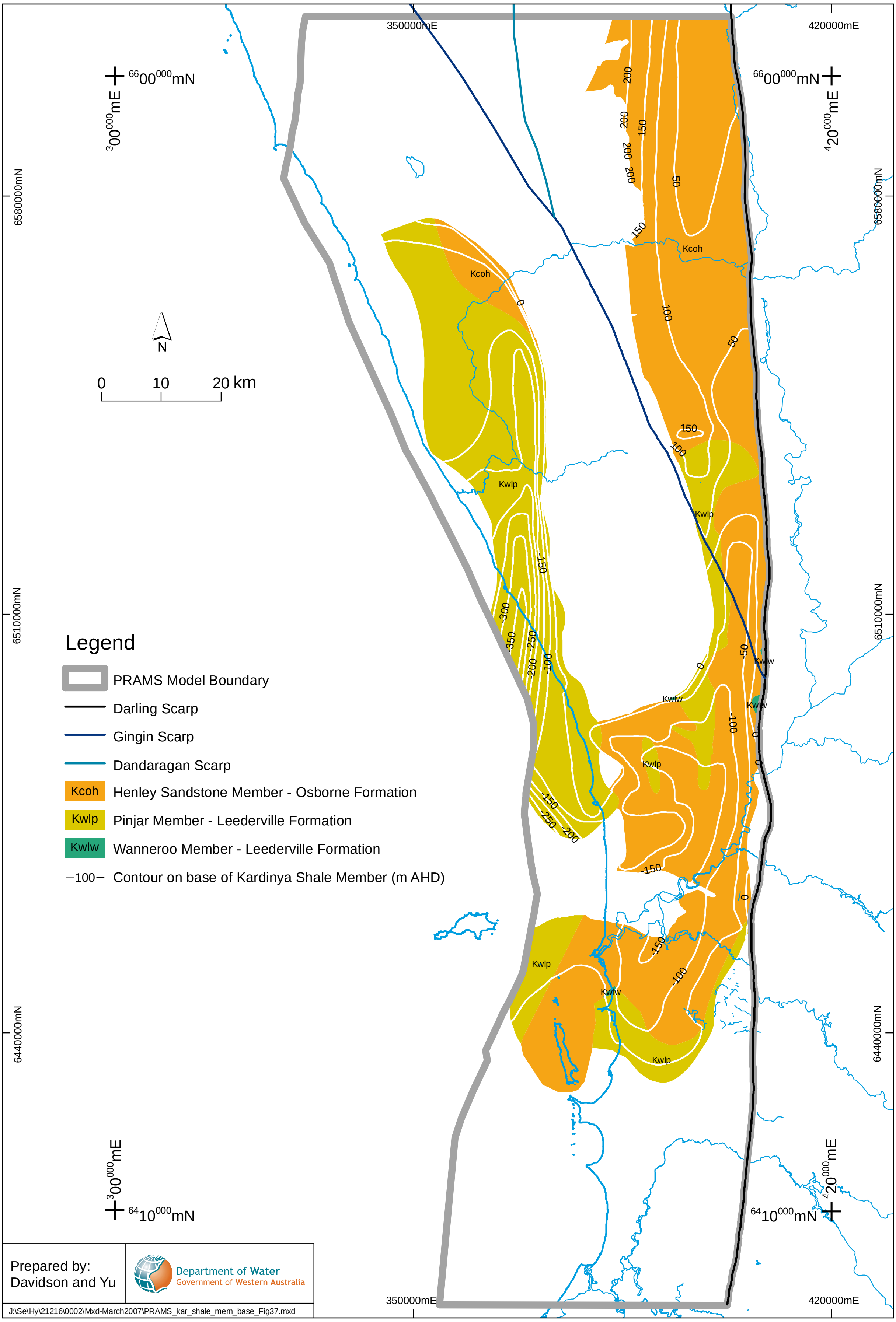


Figure 37 Kardinya Shale Member: contours on base of unit; with strata subcrop

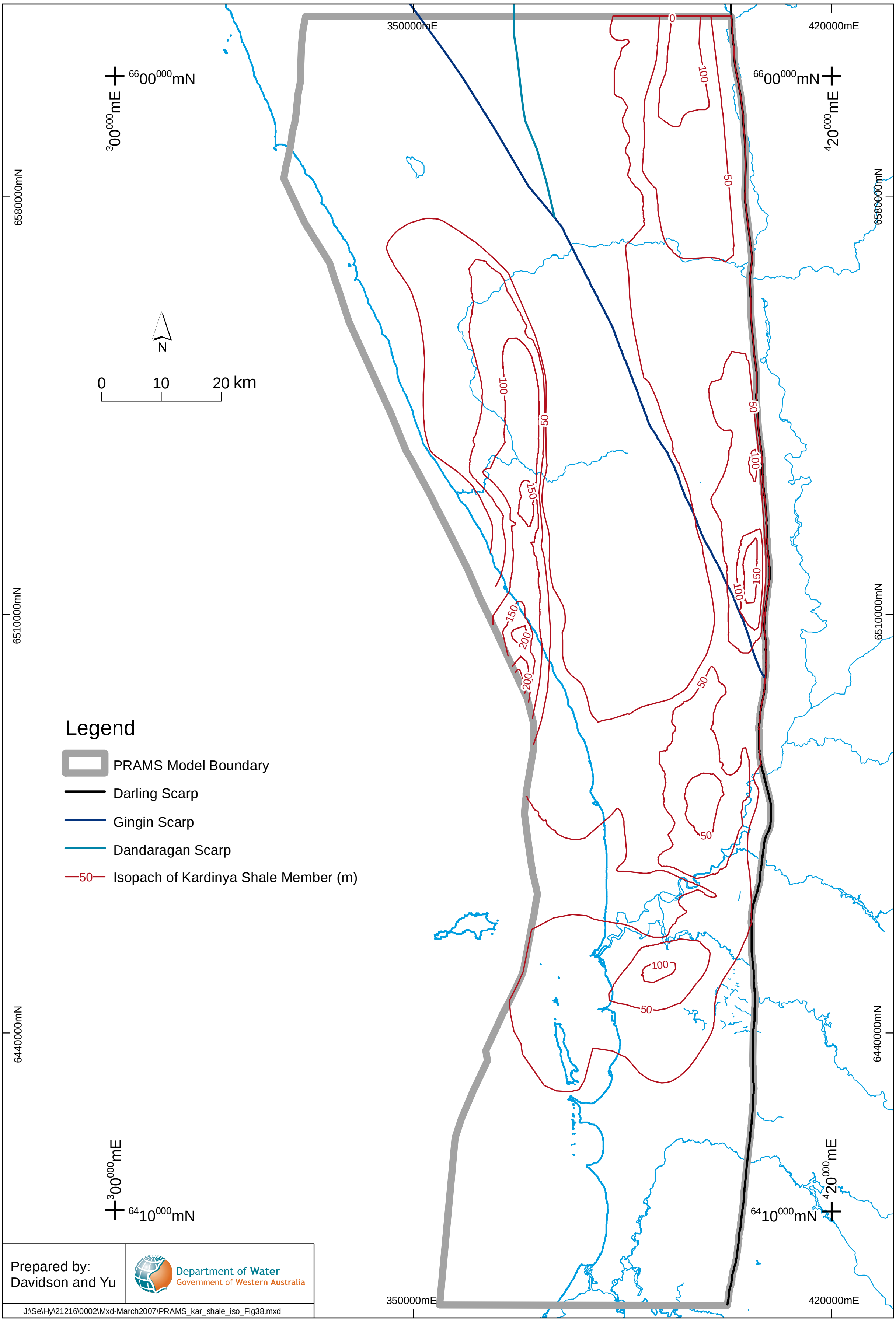


Figure 38 Kardinya Shale Member: isopachs

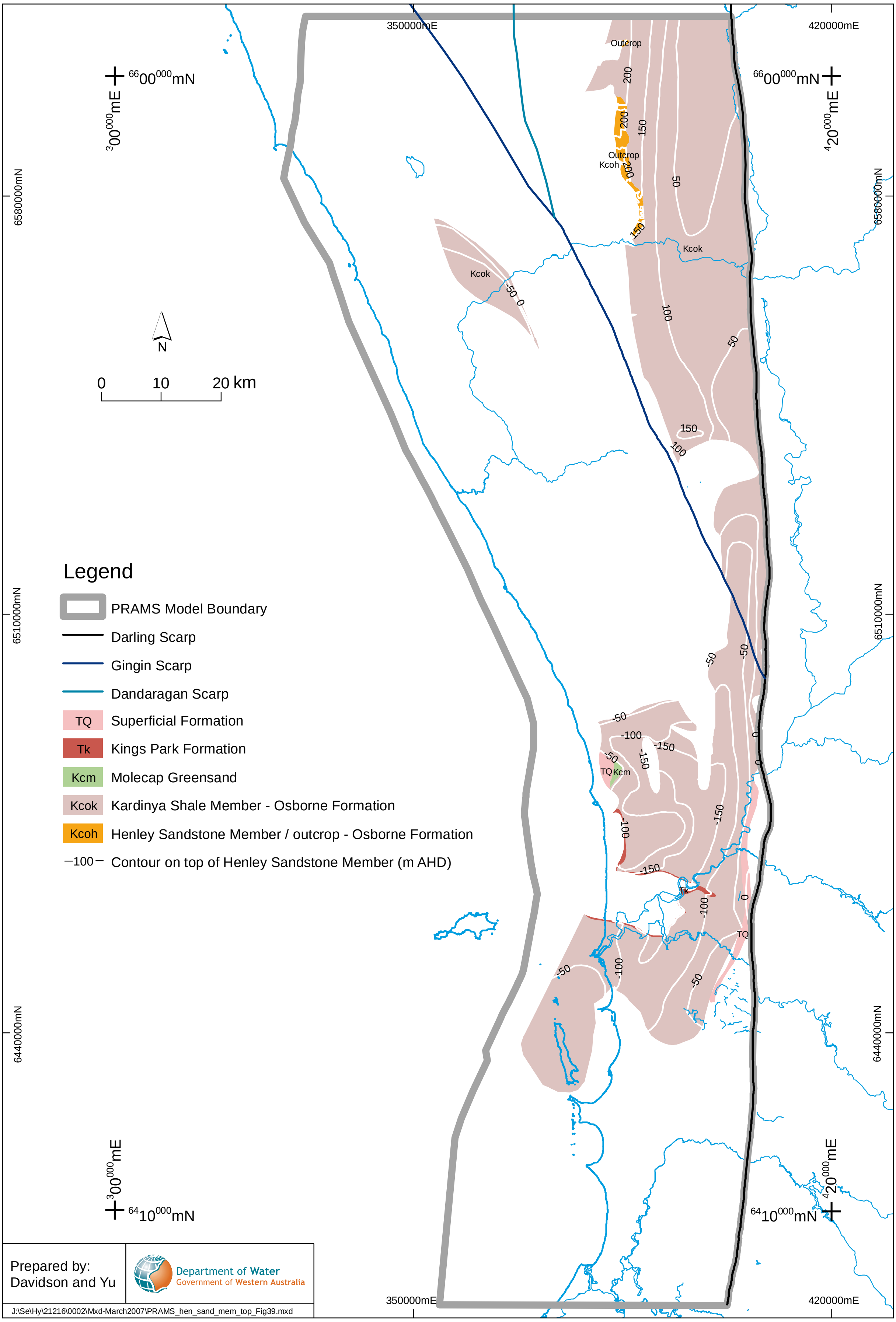


Figure 39 Henley Sandstone Member: contours on top of unit; with overlying strata

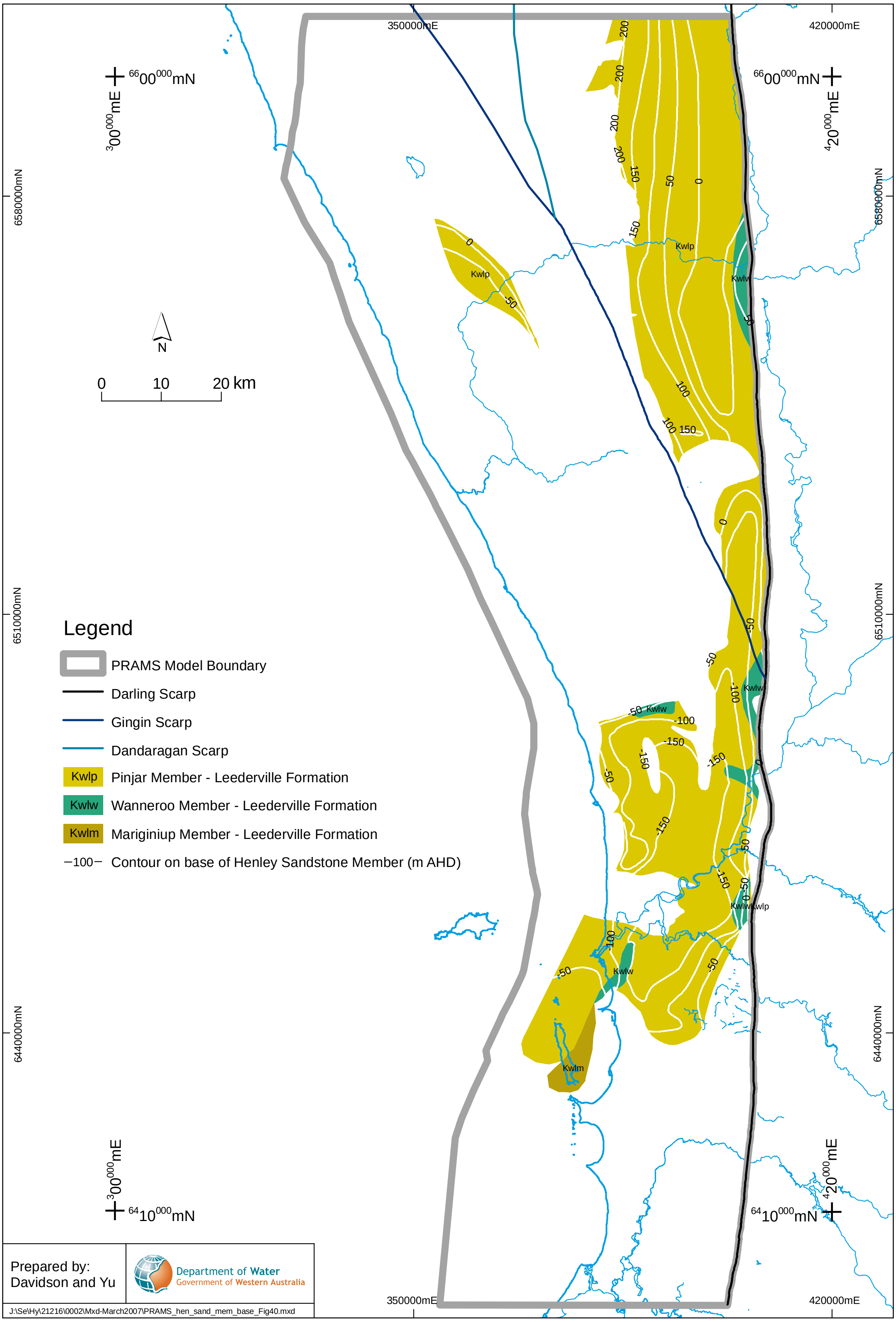


Figure 40 Henley Sandstone Member: contours on base of unit; with strata subcrop

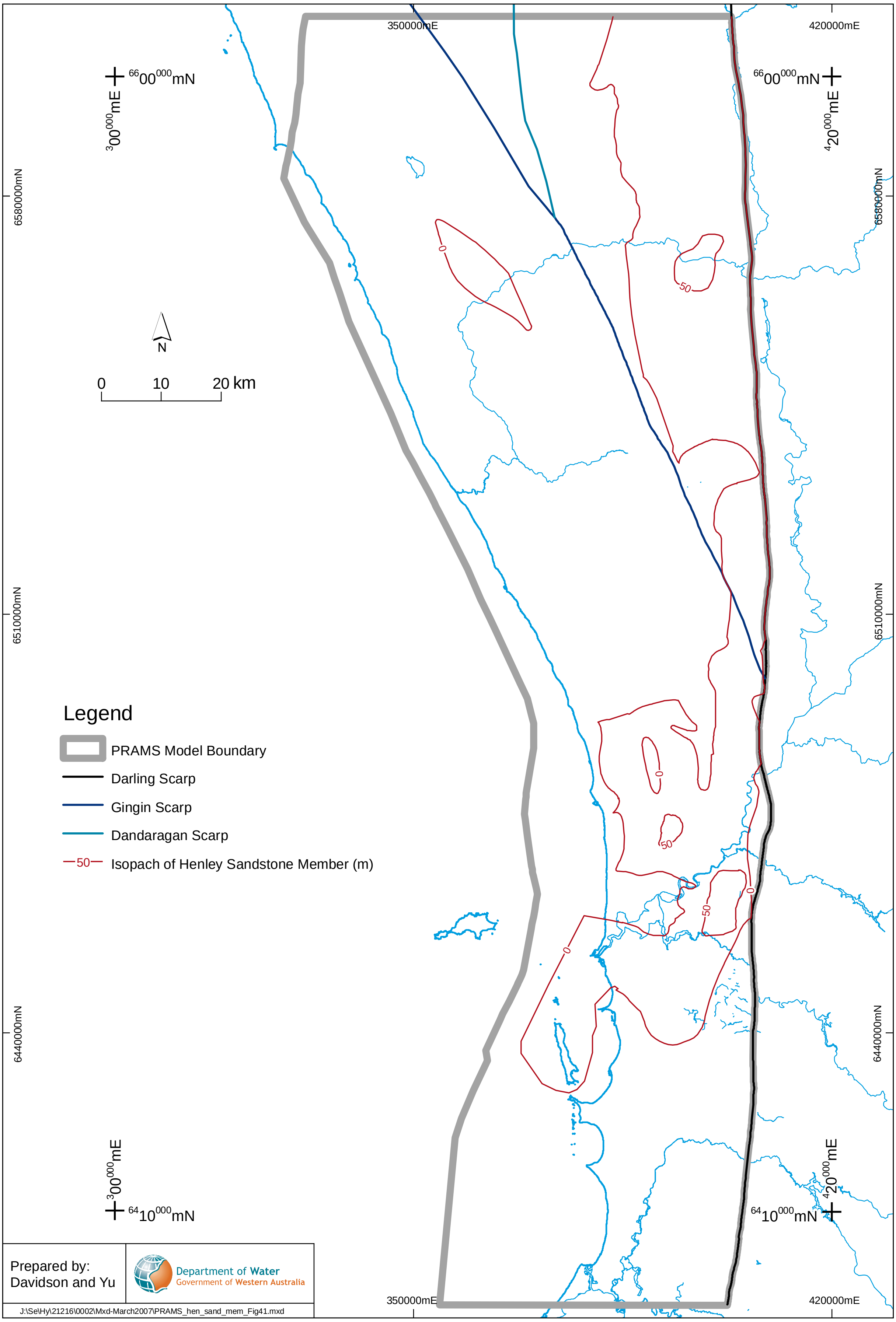


Figure 41 Henley Sandstone Member: isopachs

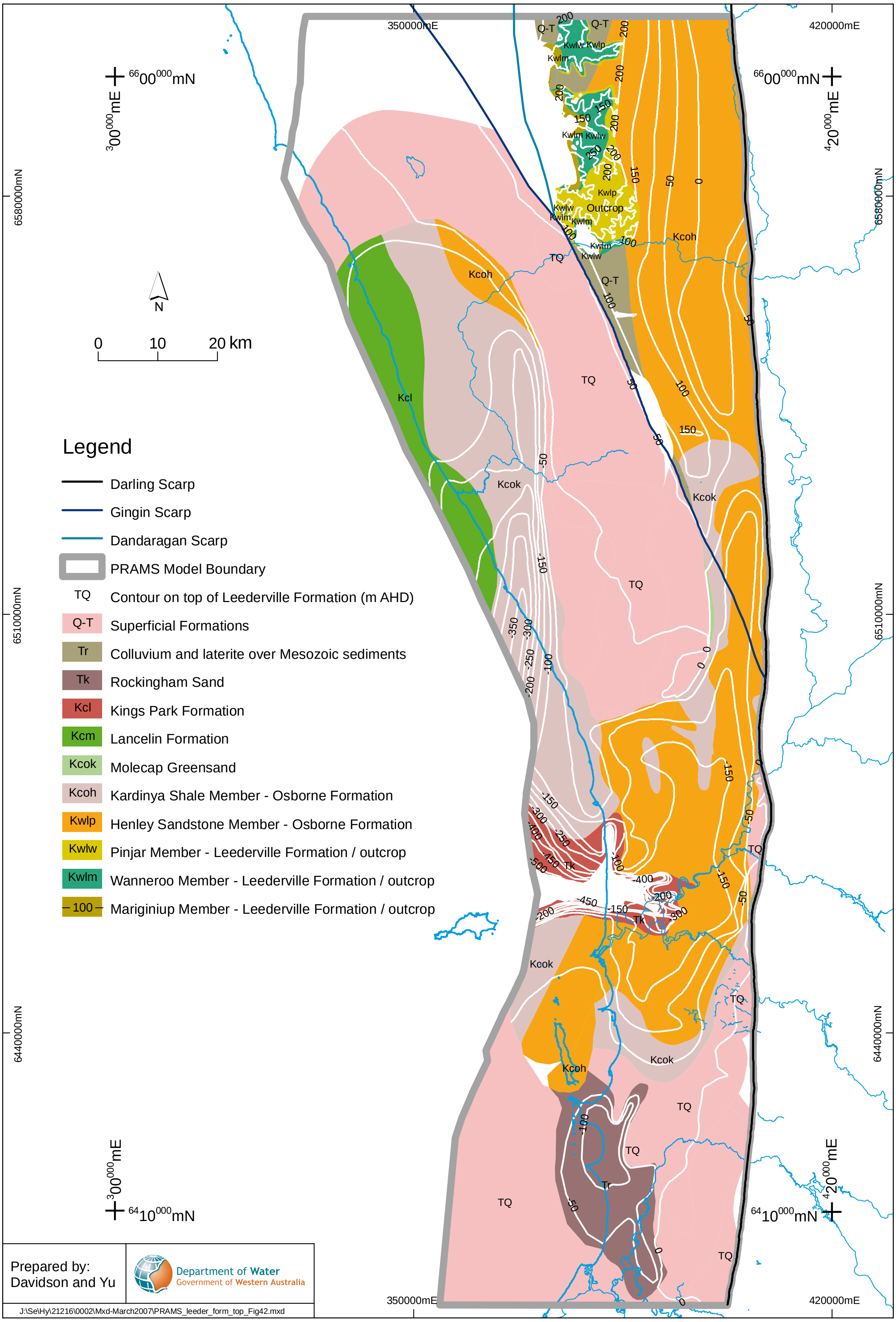


Figure 42 Leederville Formation: contours on top of unit; with overlying strata

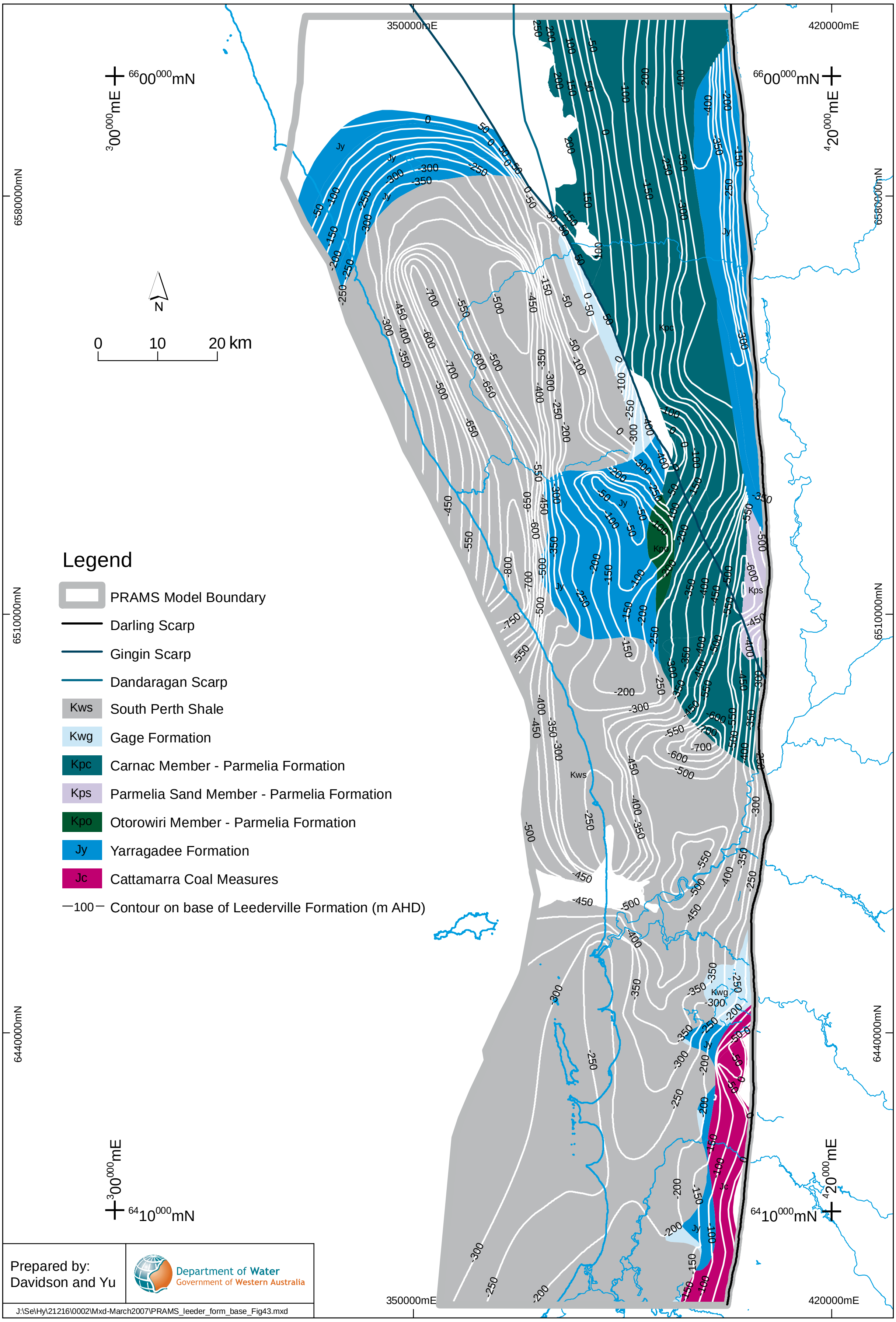


Figure 43 Leederville Formation: contours on base of unit; with strata subcrop

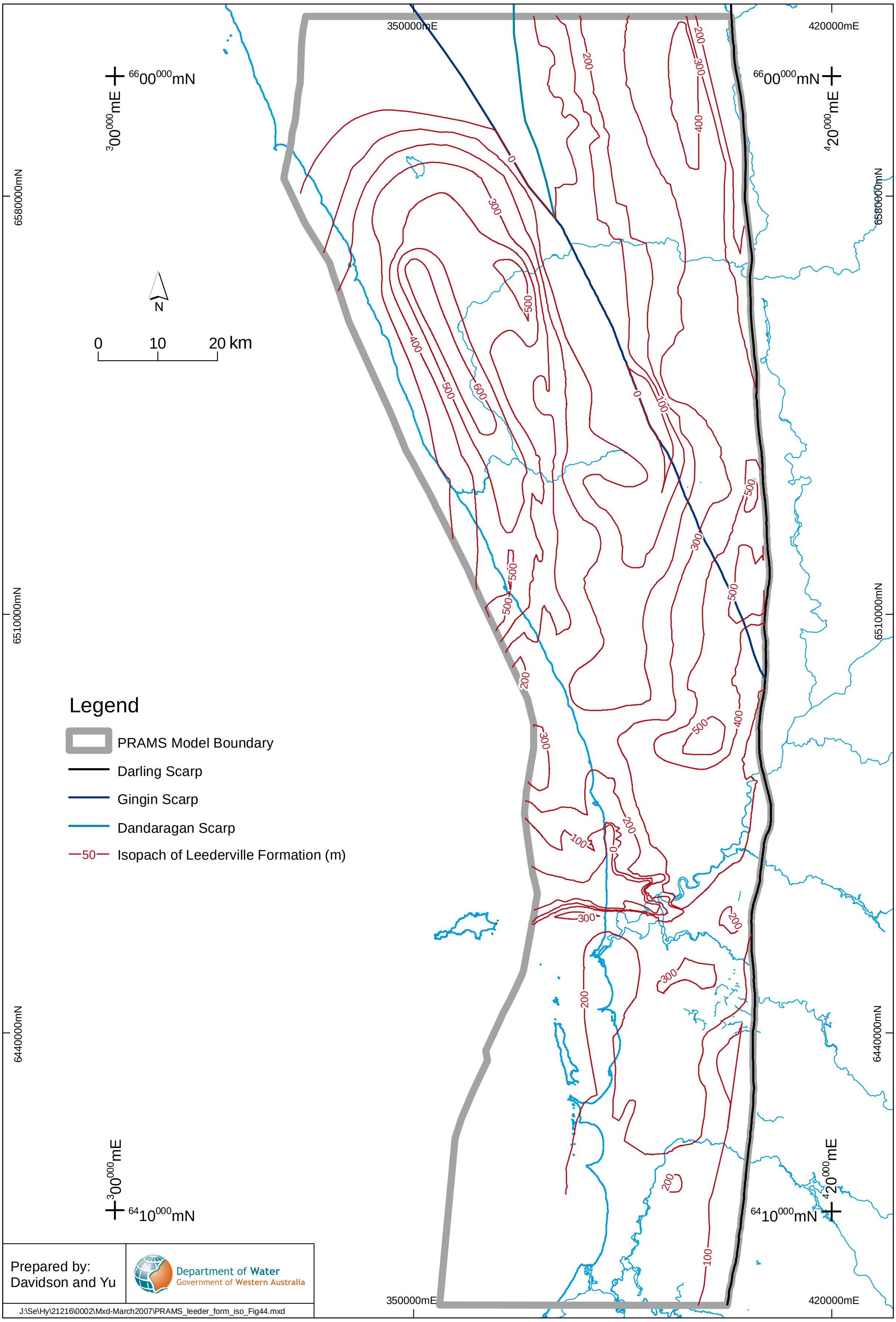


Figure 44 Leederville Formation: isopachs

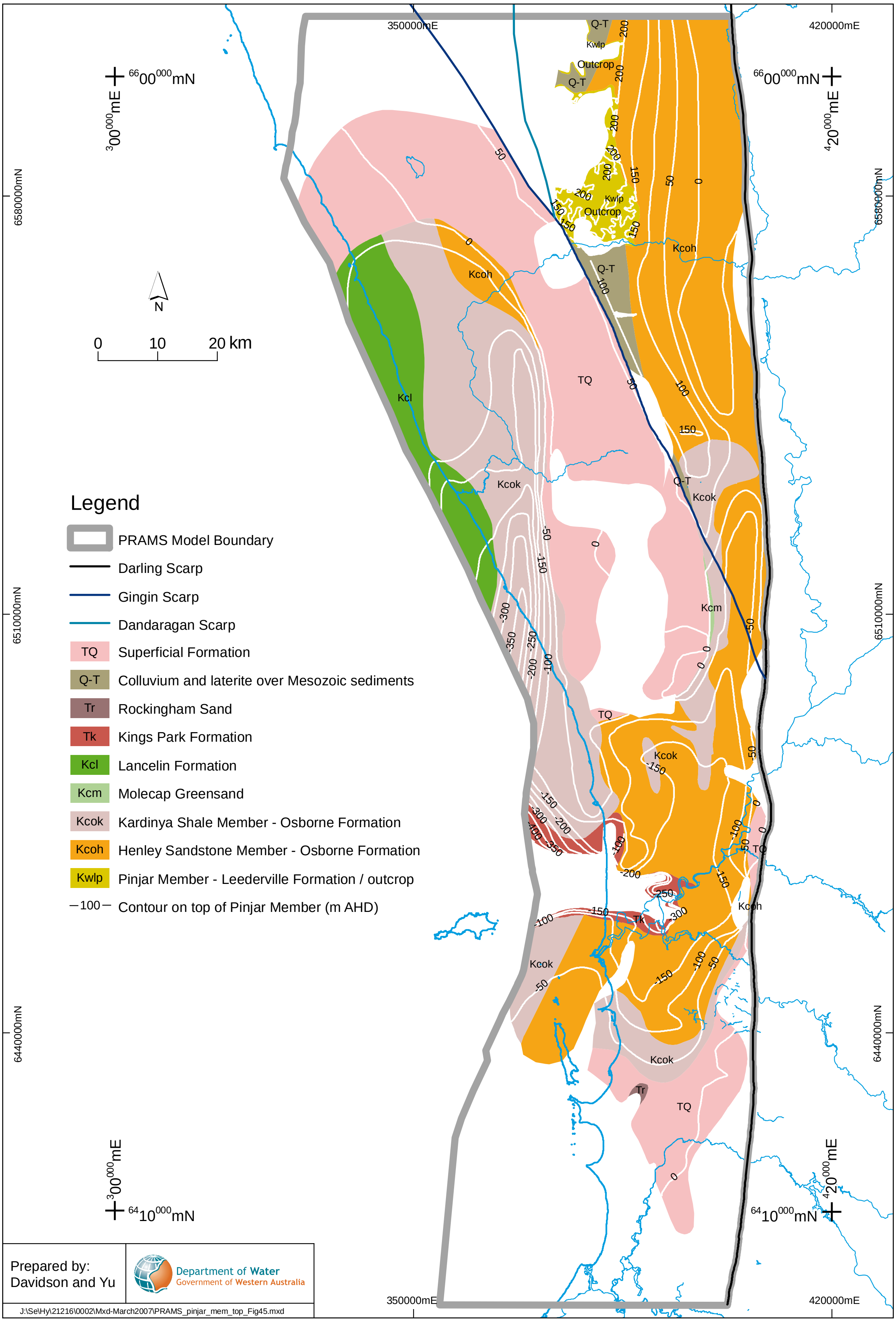


Figure 45 Pinjar Member: contours on top of unit; with overlying strata

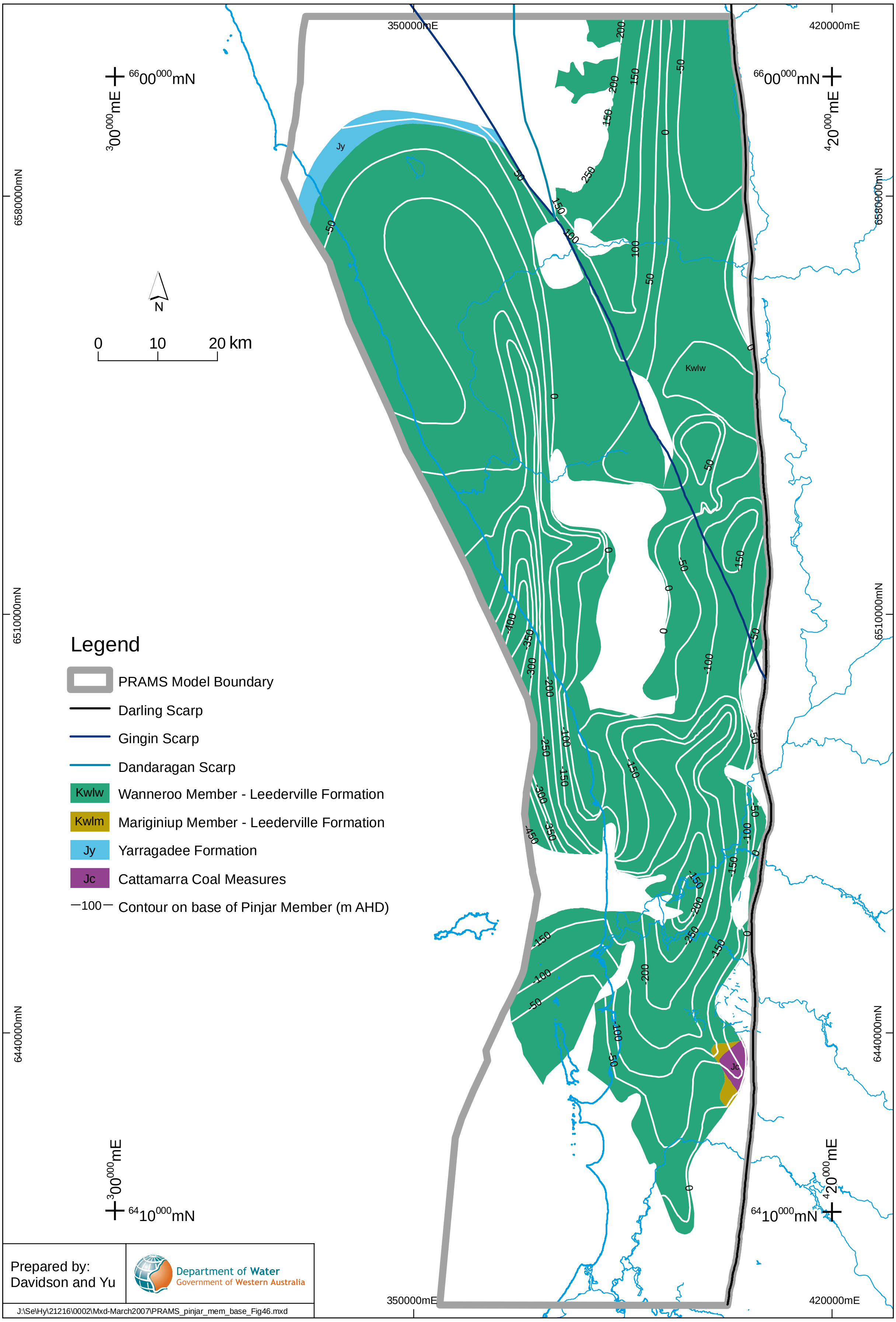


Figure 46 Pinjar Member: contours on base of unit; with strata subcrop

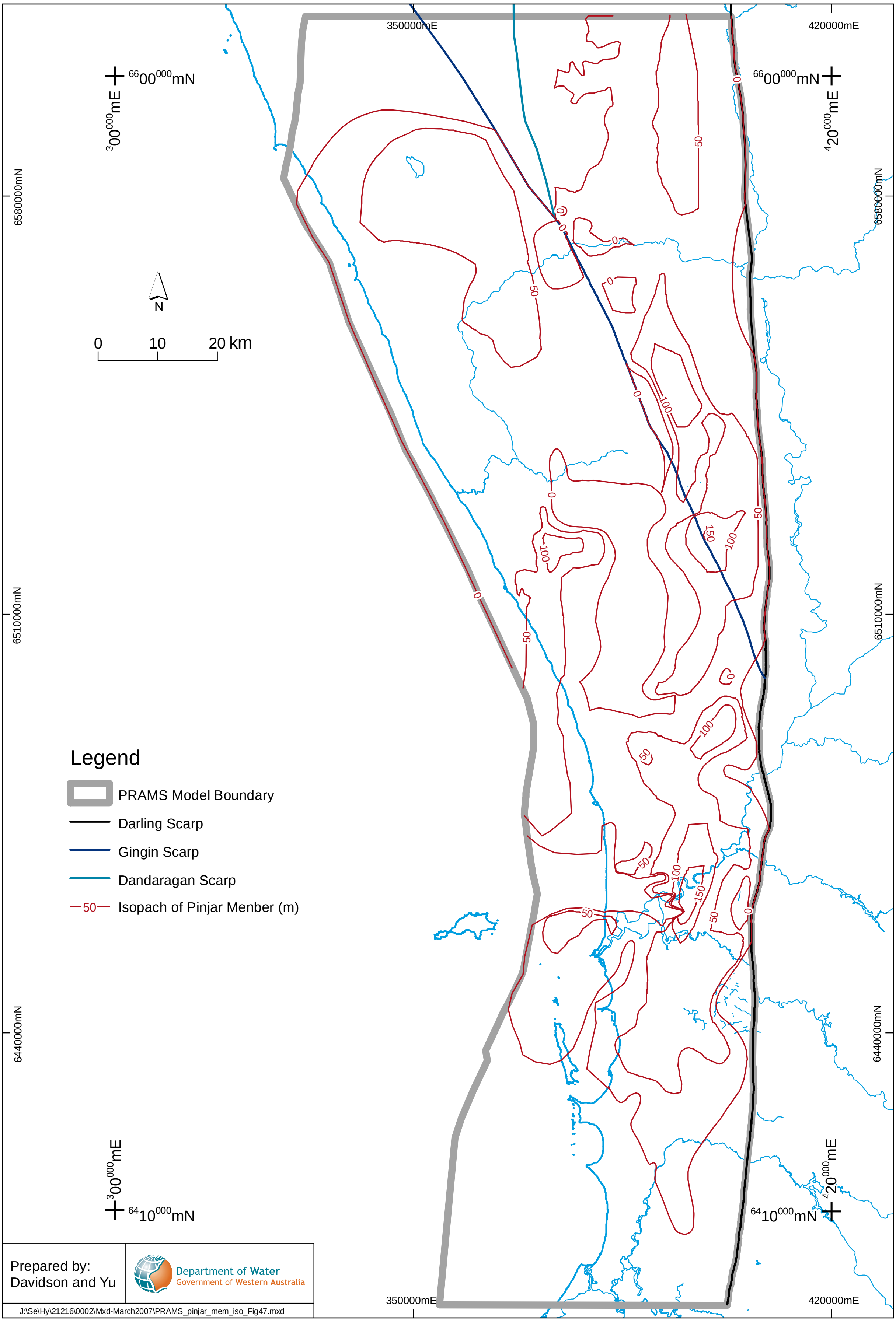


Figure 47 Pinjar Member: isopachs

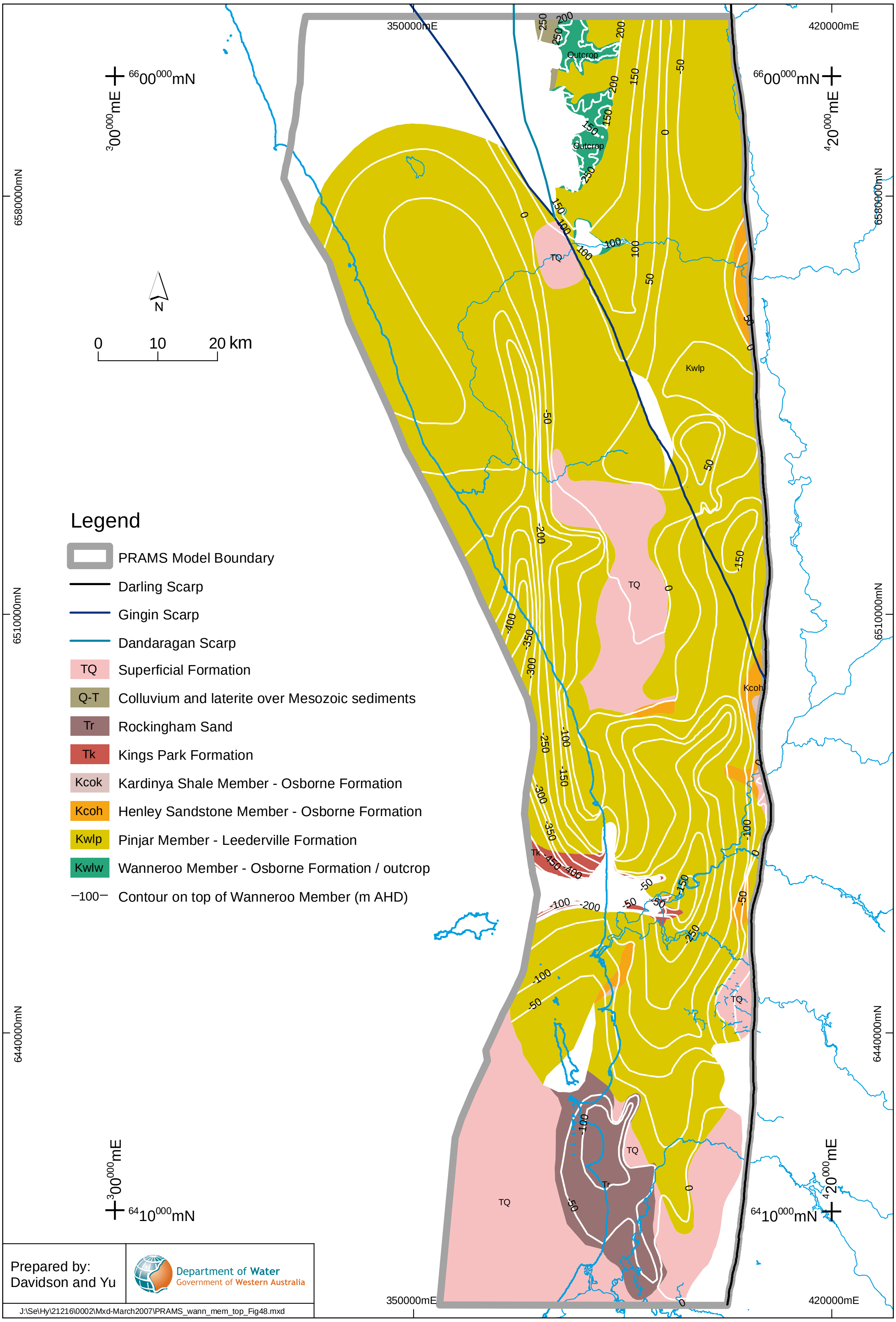


Figure 48 Wanneroo Member: contours on top of unit; with overlying strata

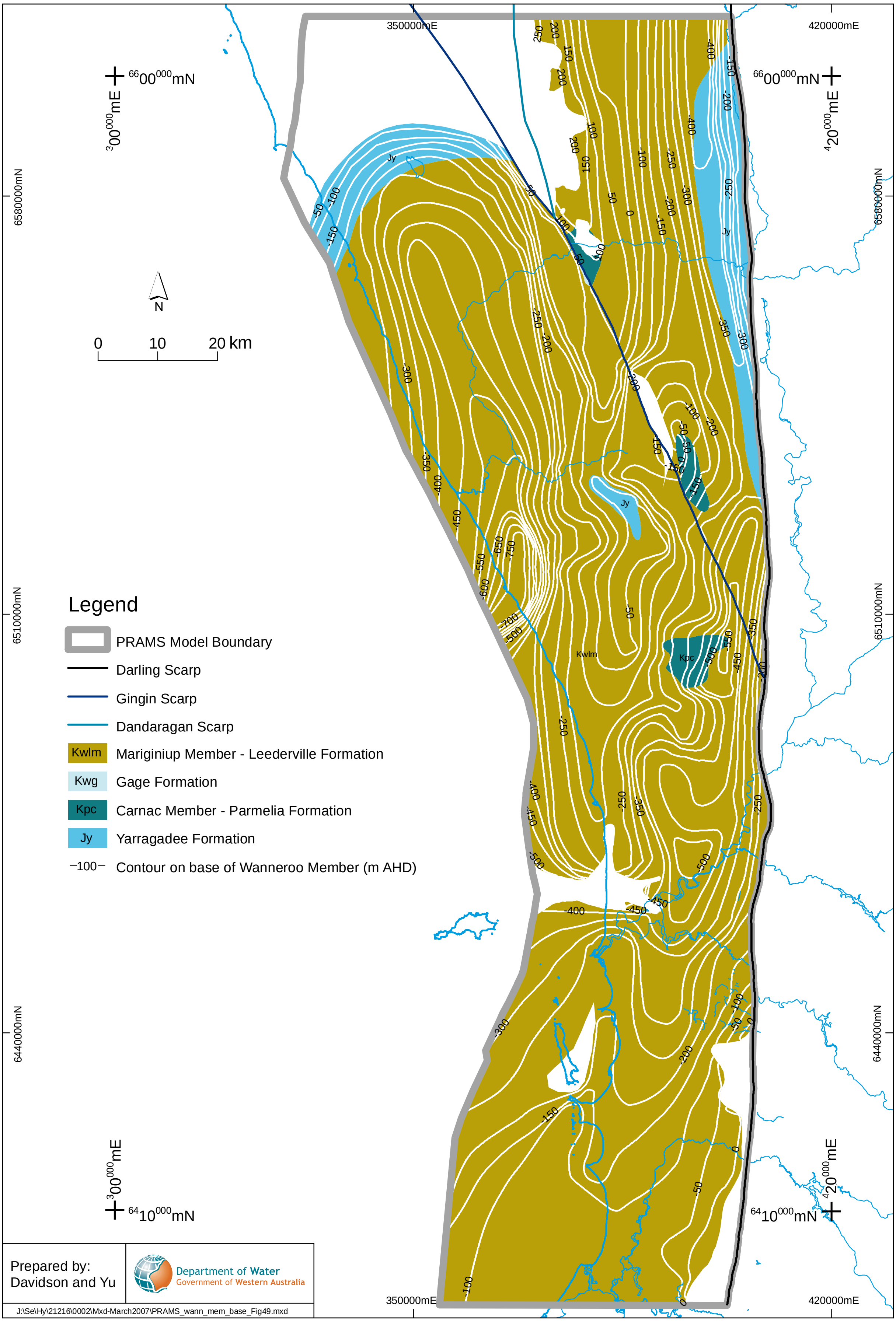


Figure 49 Wanneroo Member: contours on base of unit; with strata subcrop

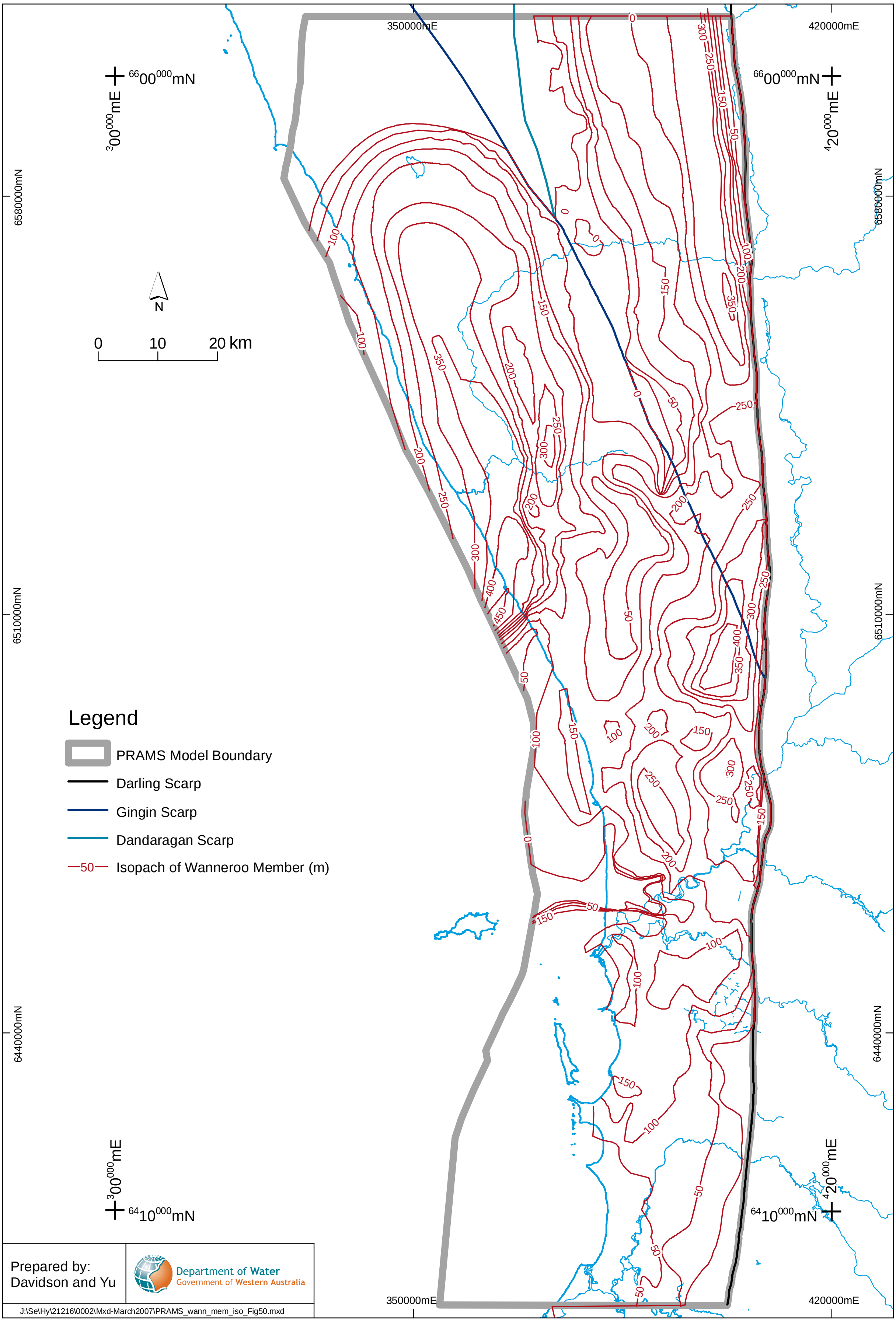


Figure 50 Wanneroo Member: isopachs

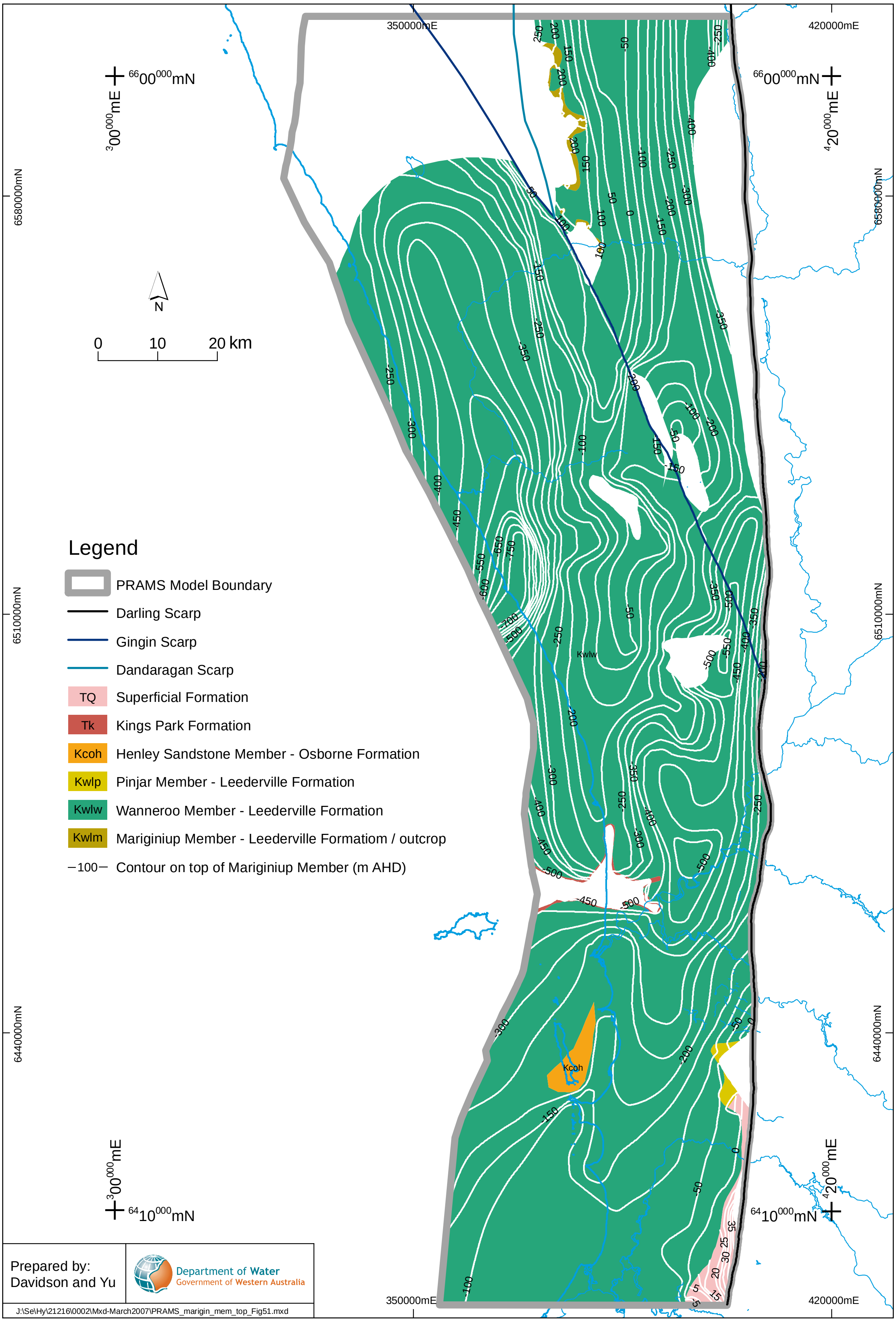


Figure 51 Mariginiup Member: contours on top of unit; with overlying strata

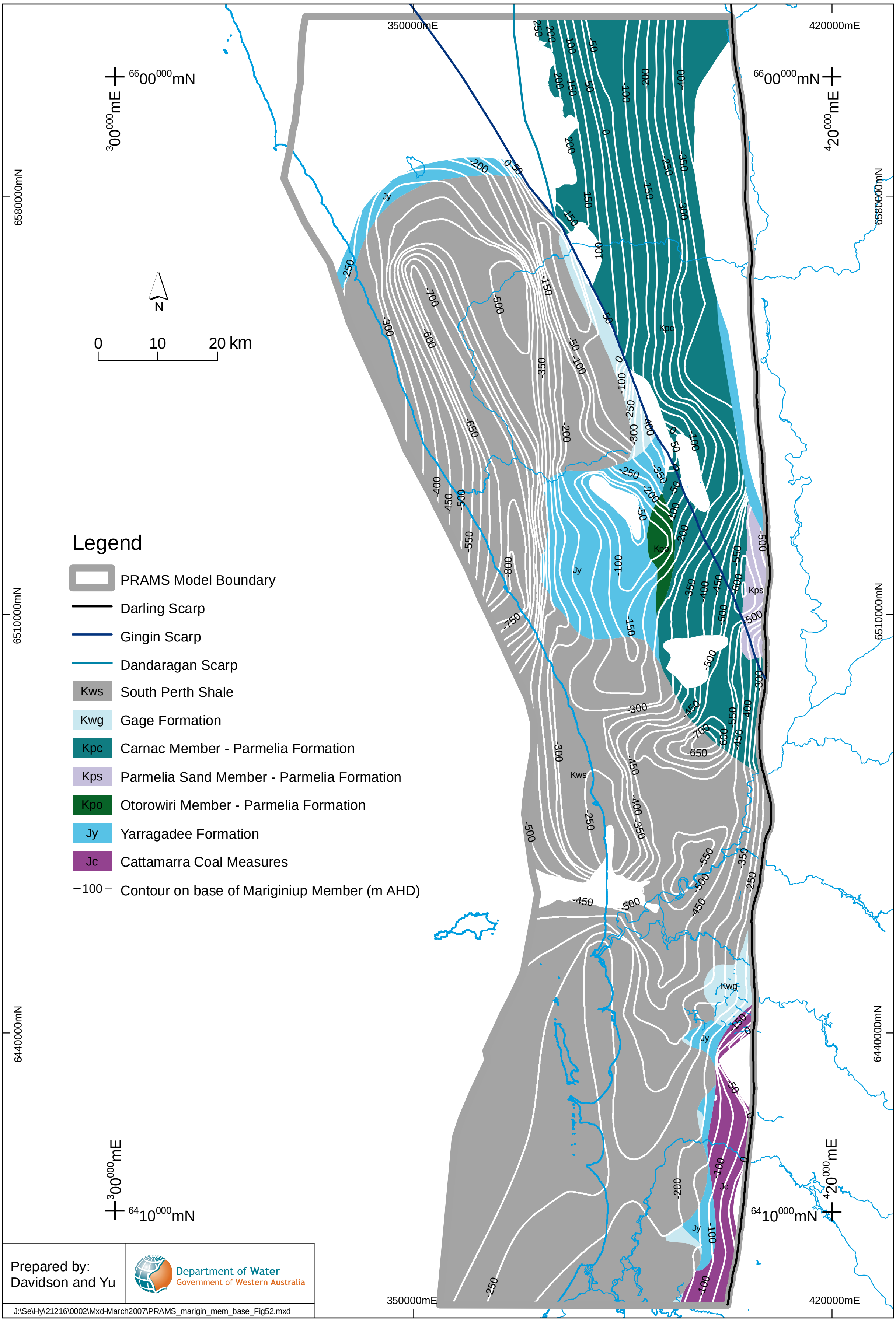


Figure 52 Mariginiup Member: contours on base of unit; with strata subcrop

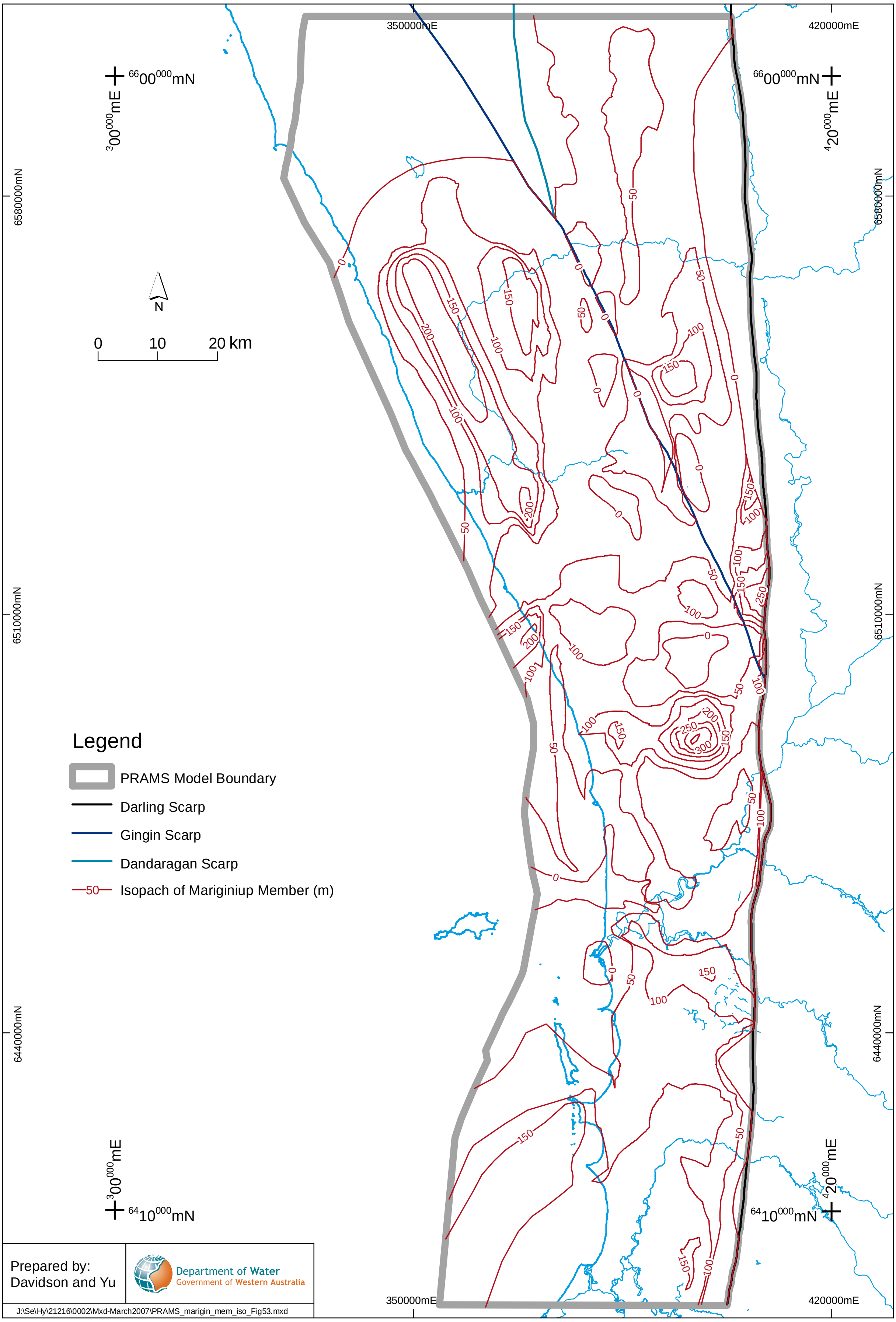


Figure 53 Mariginiup Member: isopachs

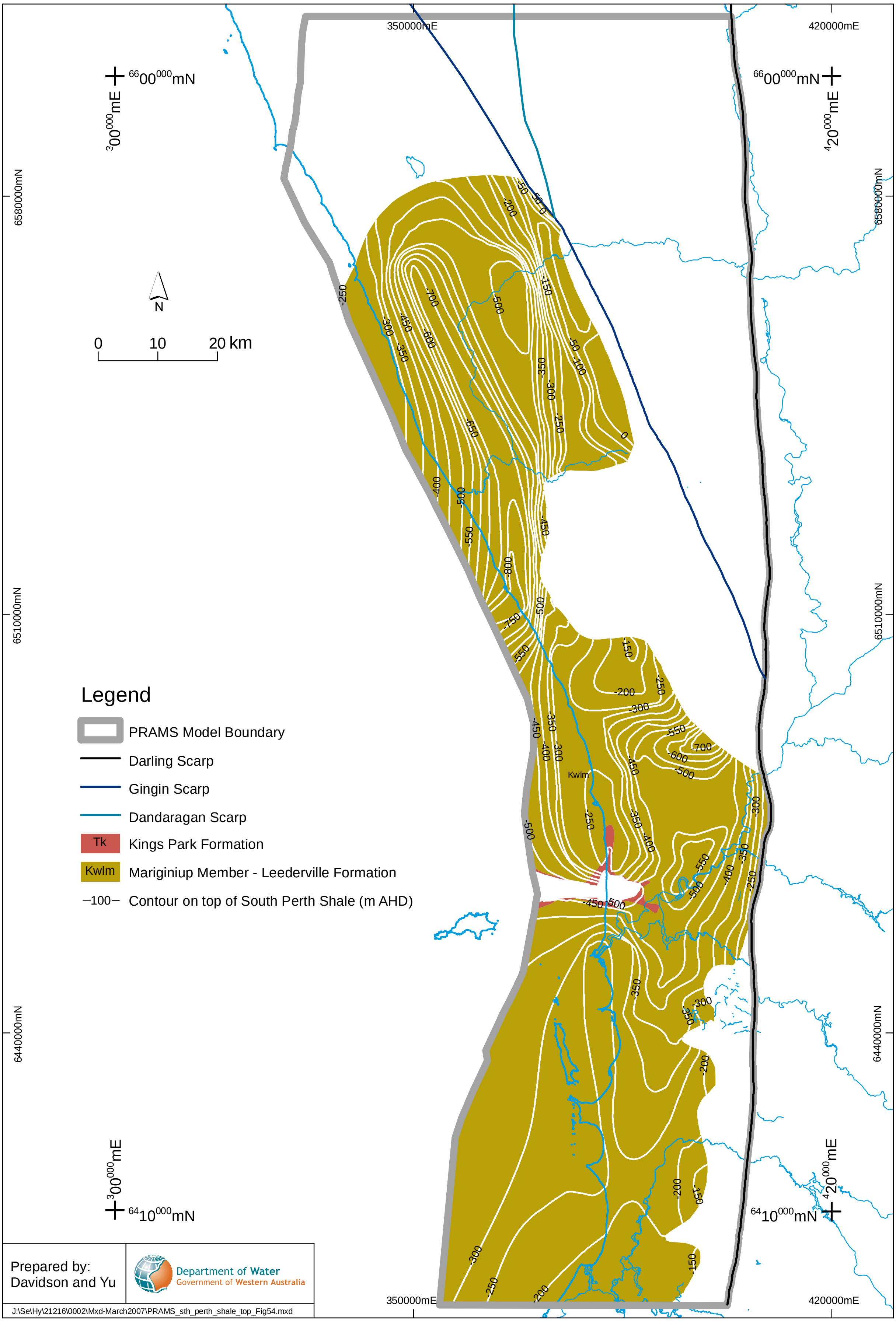


Figure 54 South Perth Shale: contours on top of unit; with overlying strata

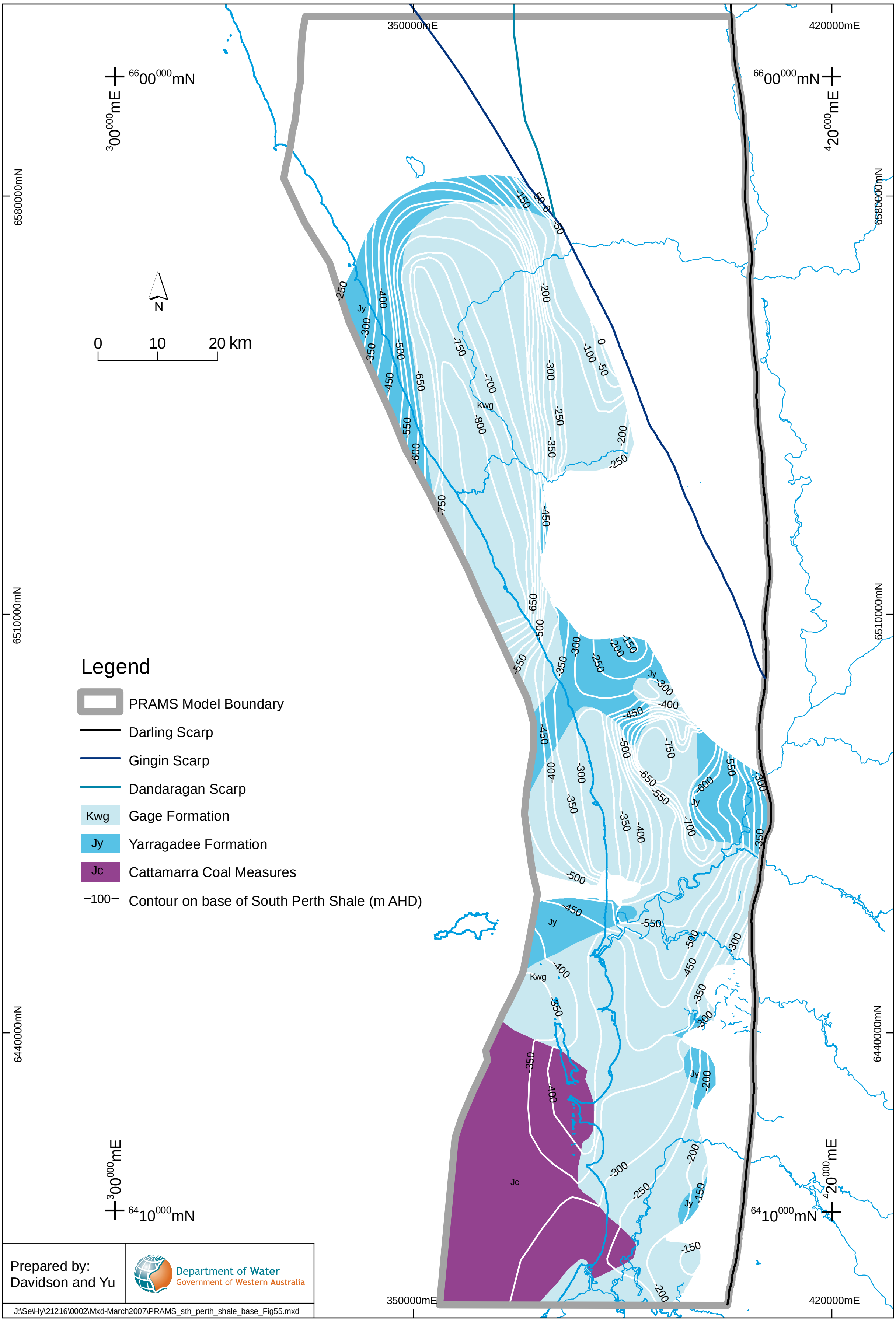


Figure 55 South Perth Shale: contours on base of unit; with strata subcrop

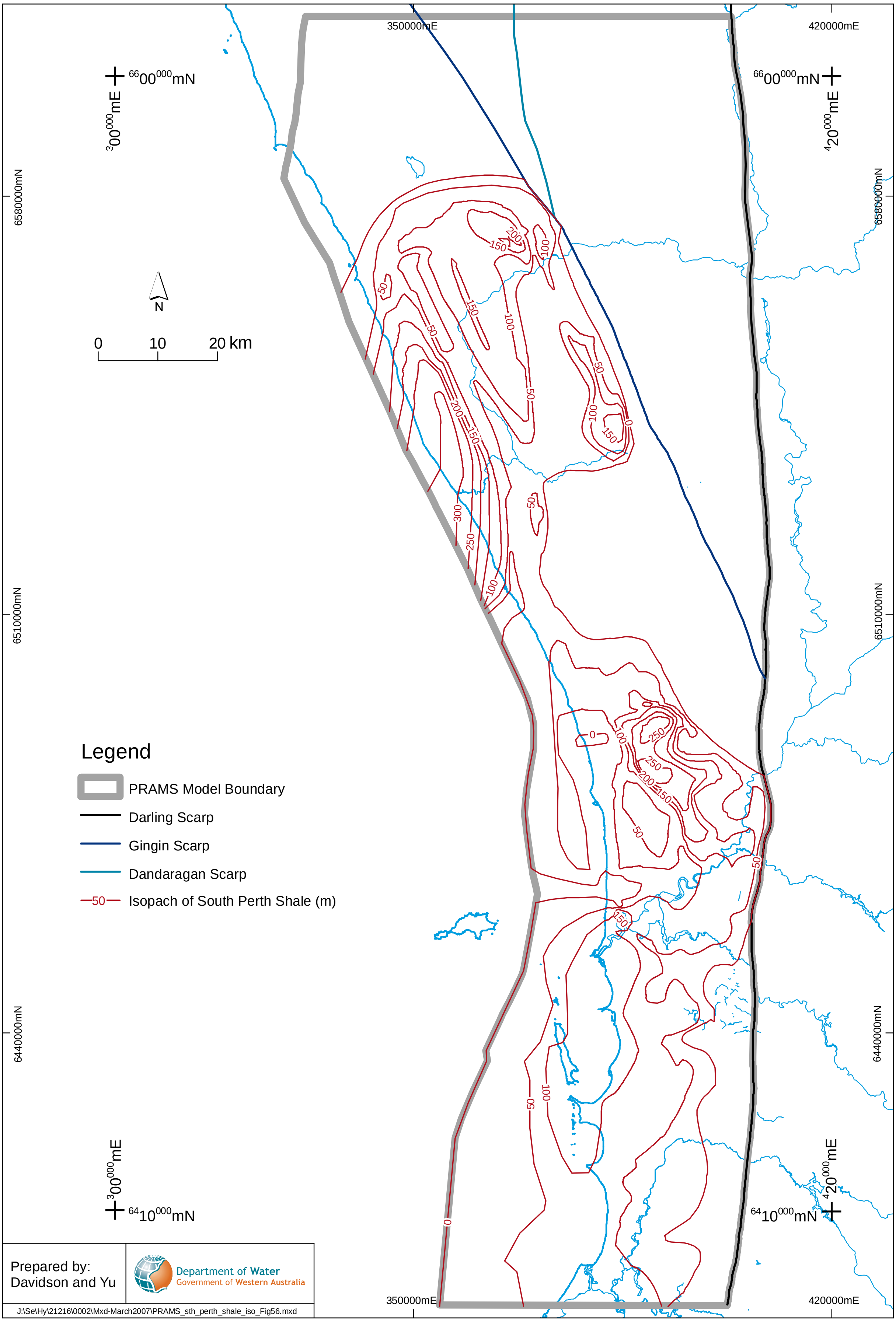


Figure 56 South Perth Shale: isopachs

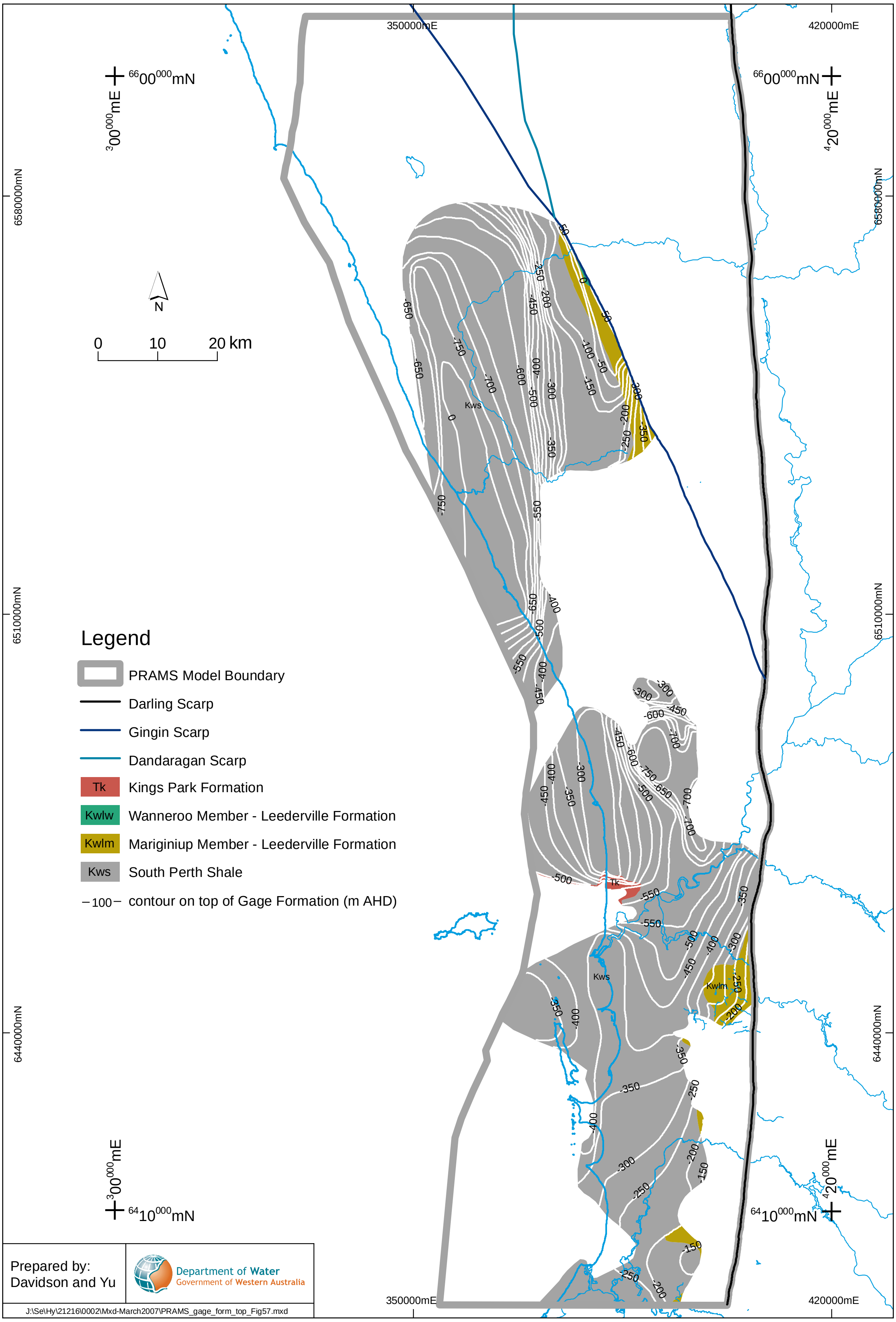


Figure 57 Gage Formation: contours on top of unit; with overlying strata

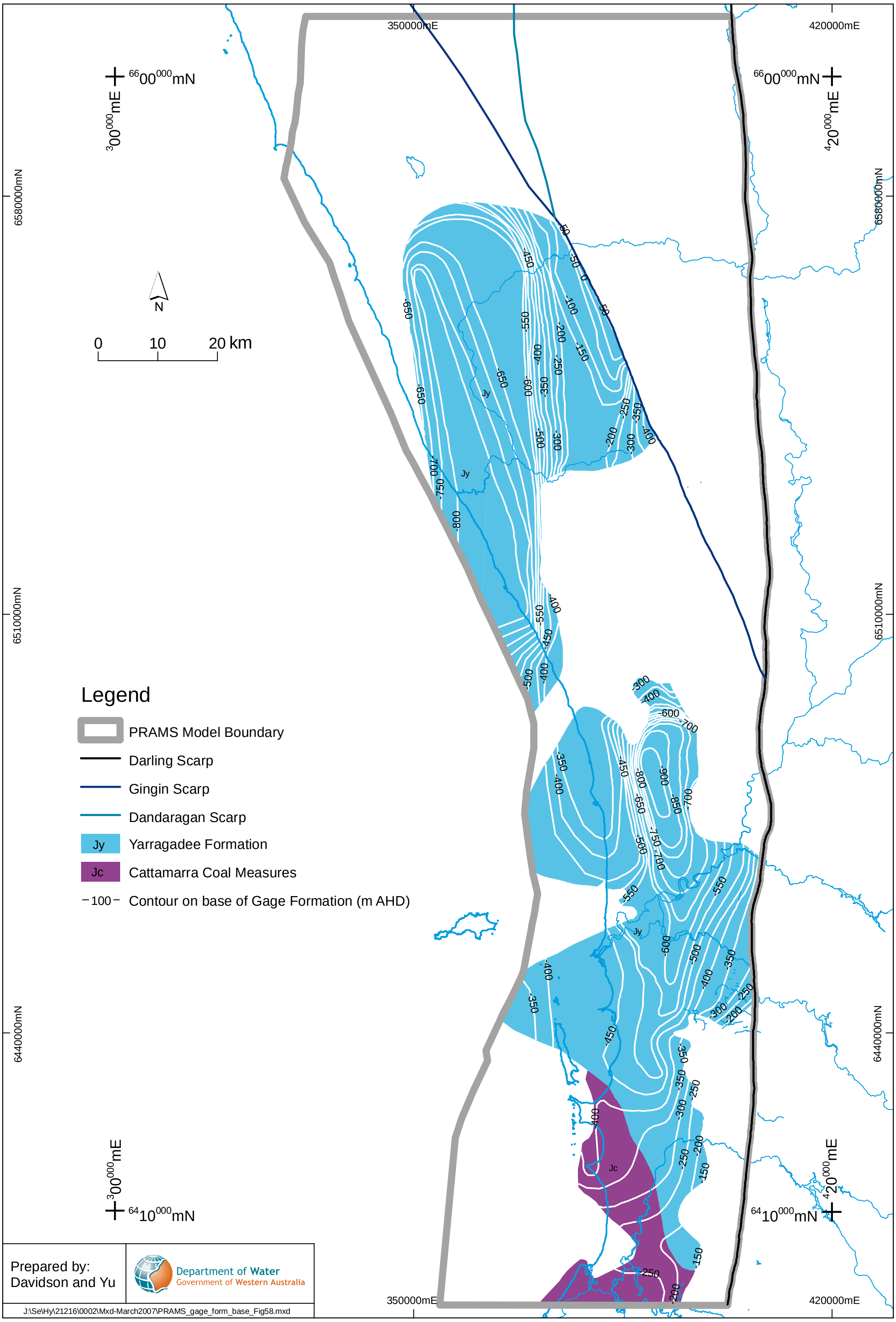


Figure 58 Gage Formation: contours on base of unit; with strata subcrop

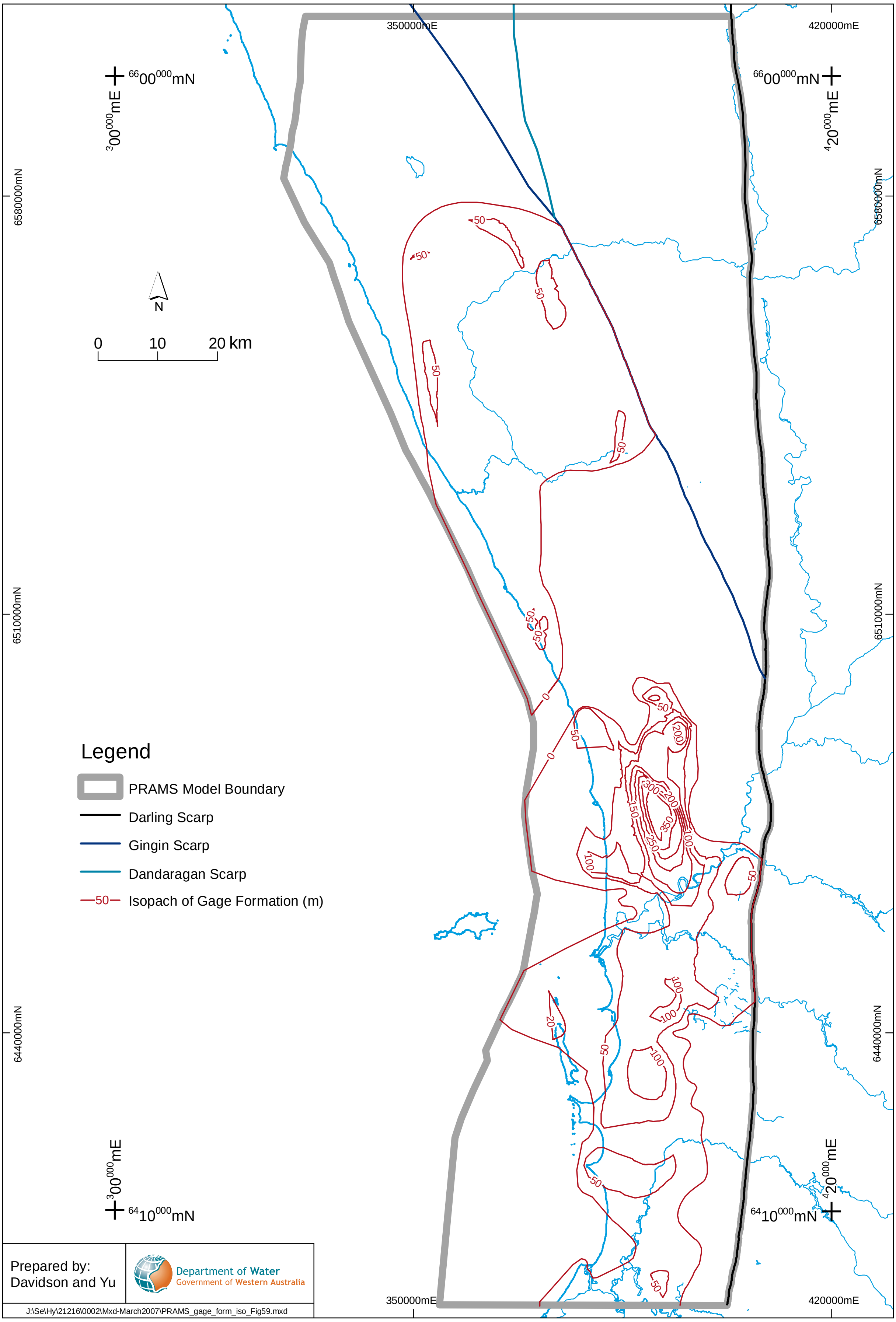


Figure 59 Gage Formation: isopachs

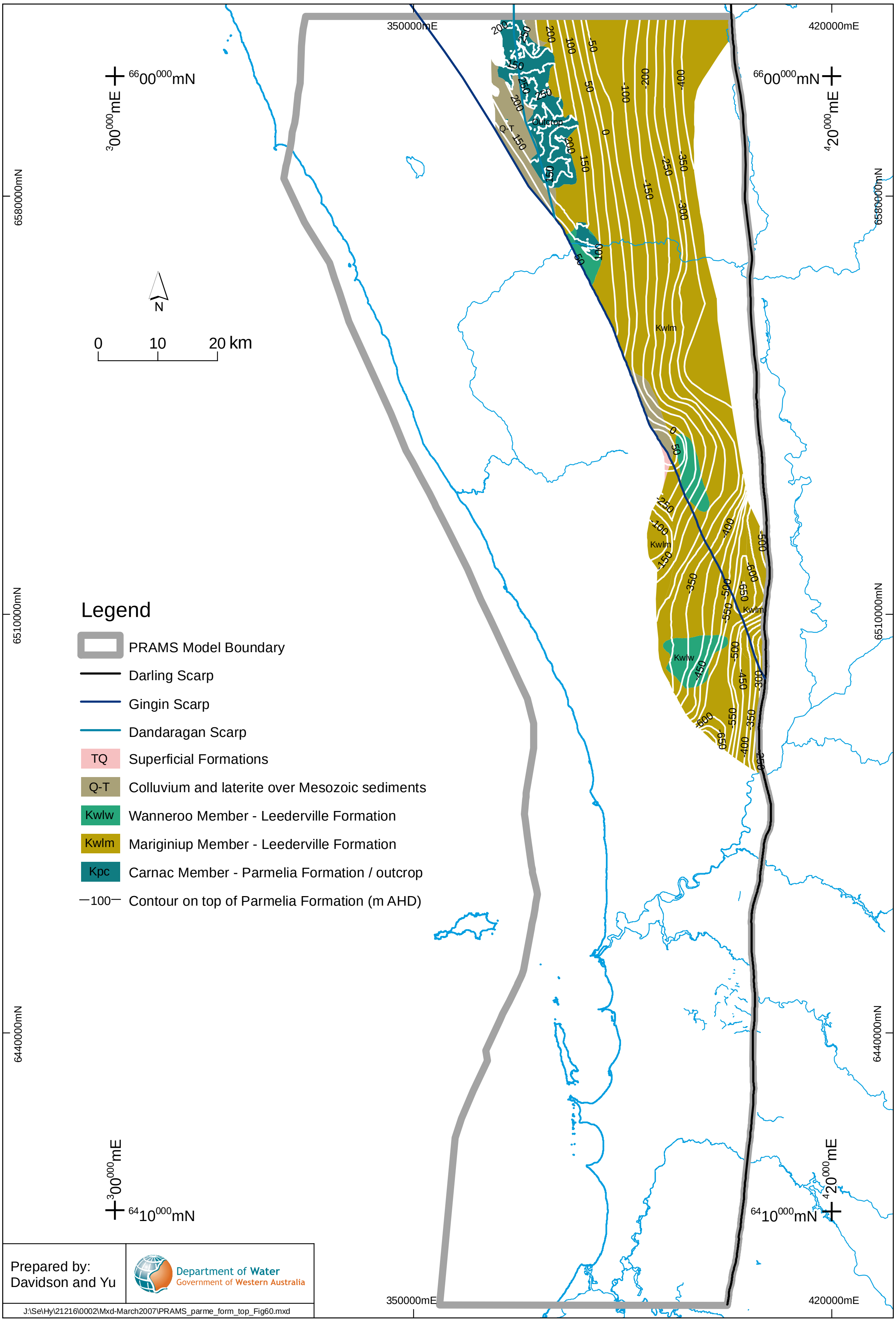


Figure 60 Parmelia Formation: contours on top of unit; with overlying strata

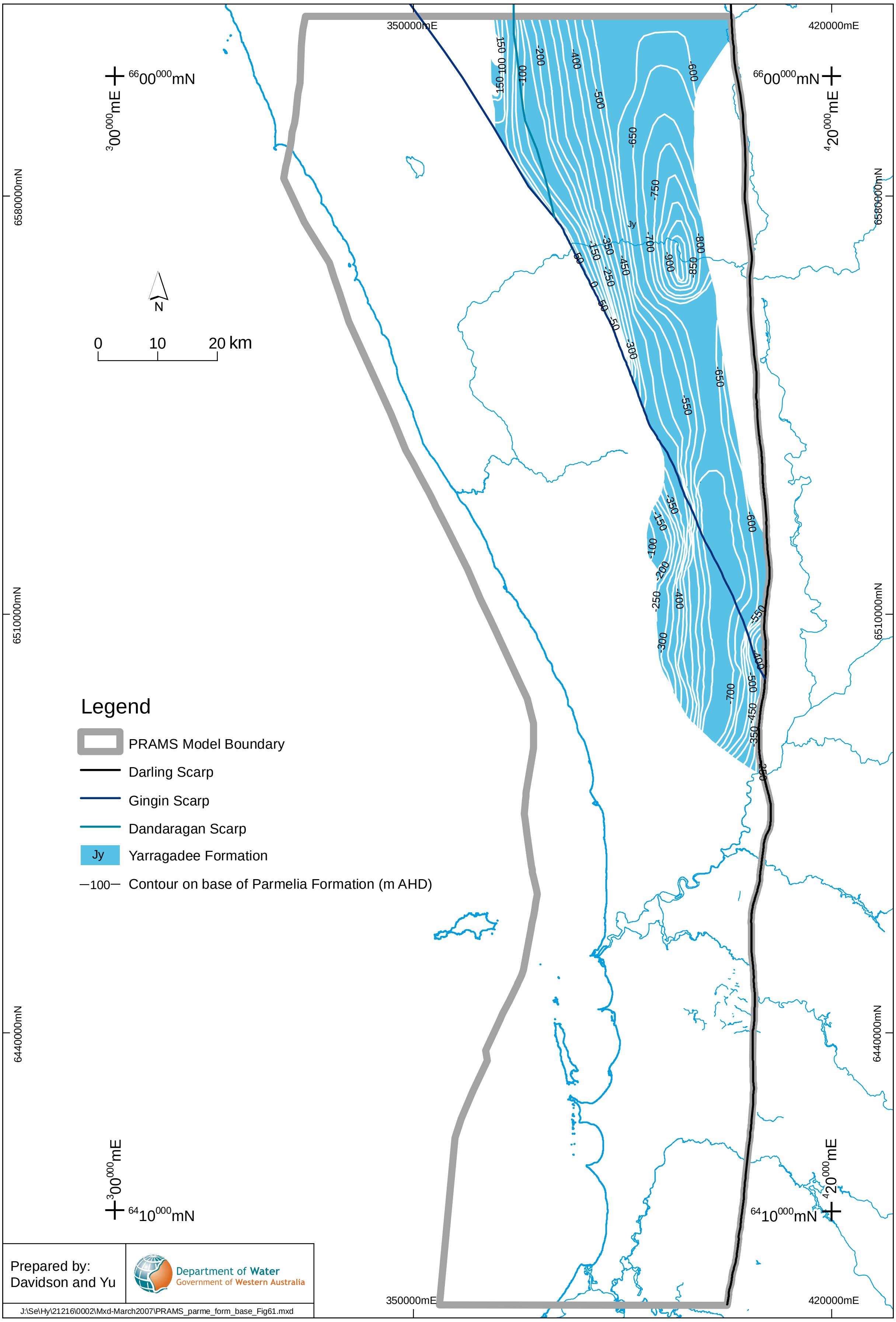


Figure 61 Parmelia Formation: contours on base of unit; with strata subcrop

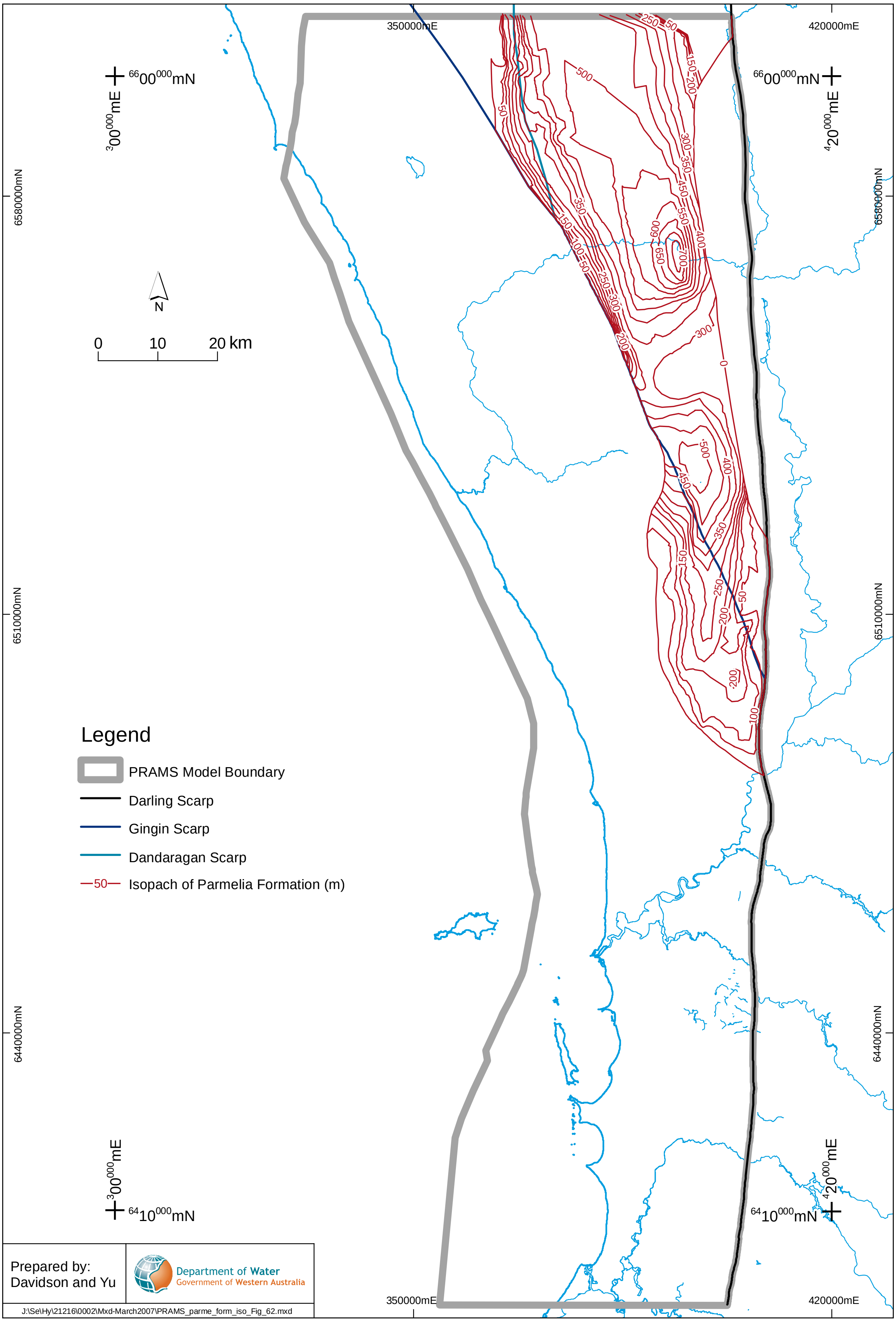


Figure 62 Parmelia Formation: isopachs

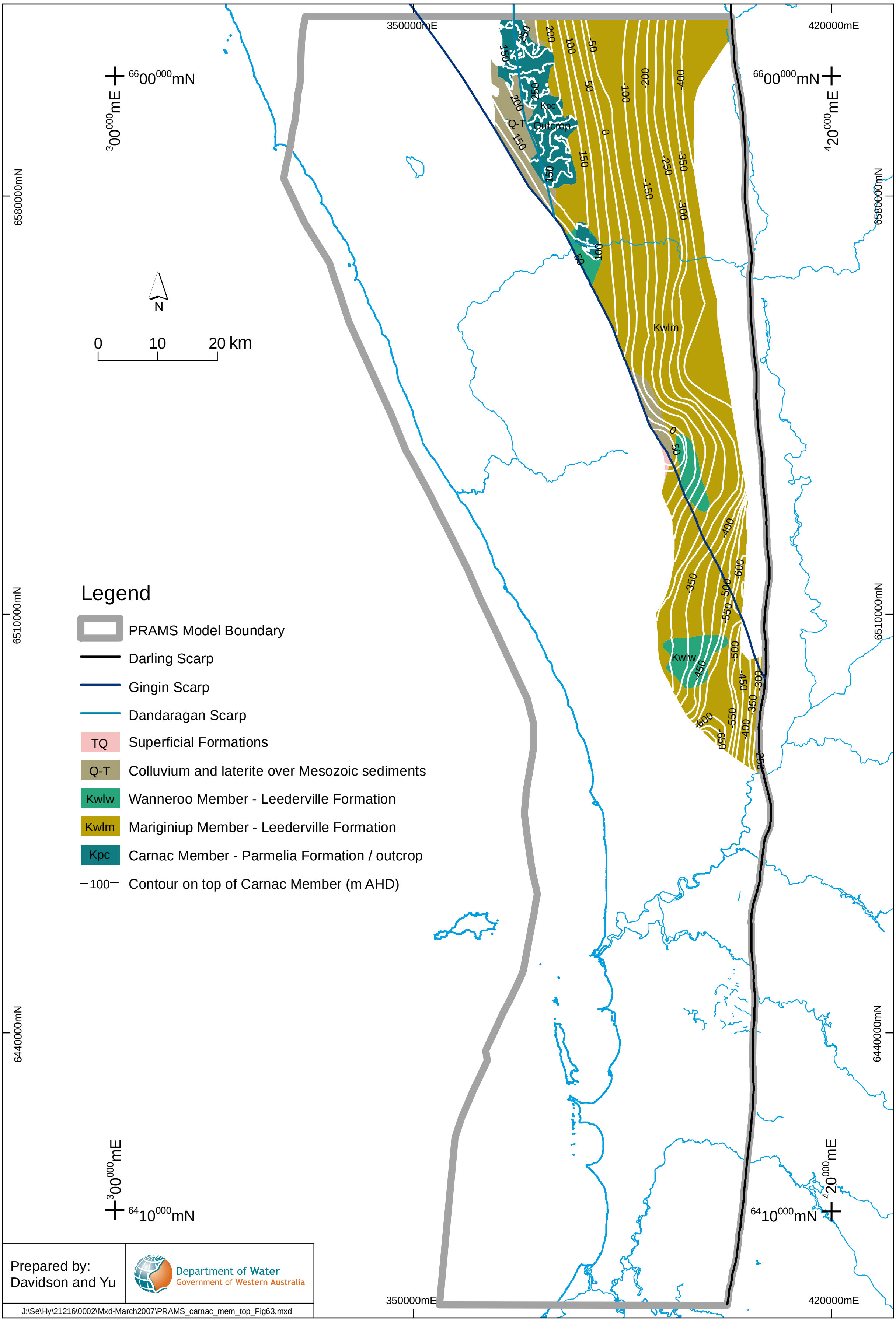


Figure 63 Carnac Member: contours on top of unit; with overlying strata

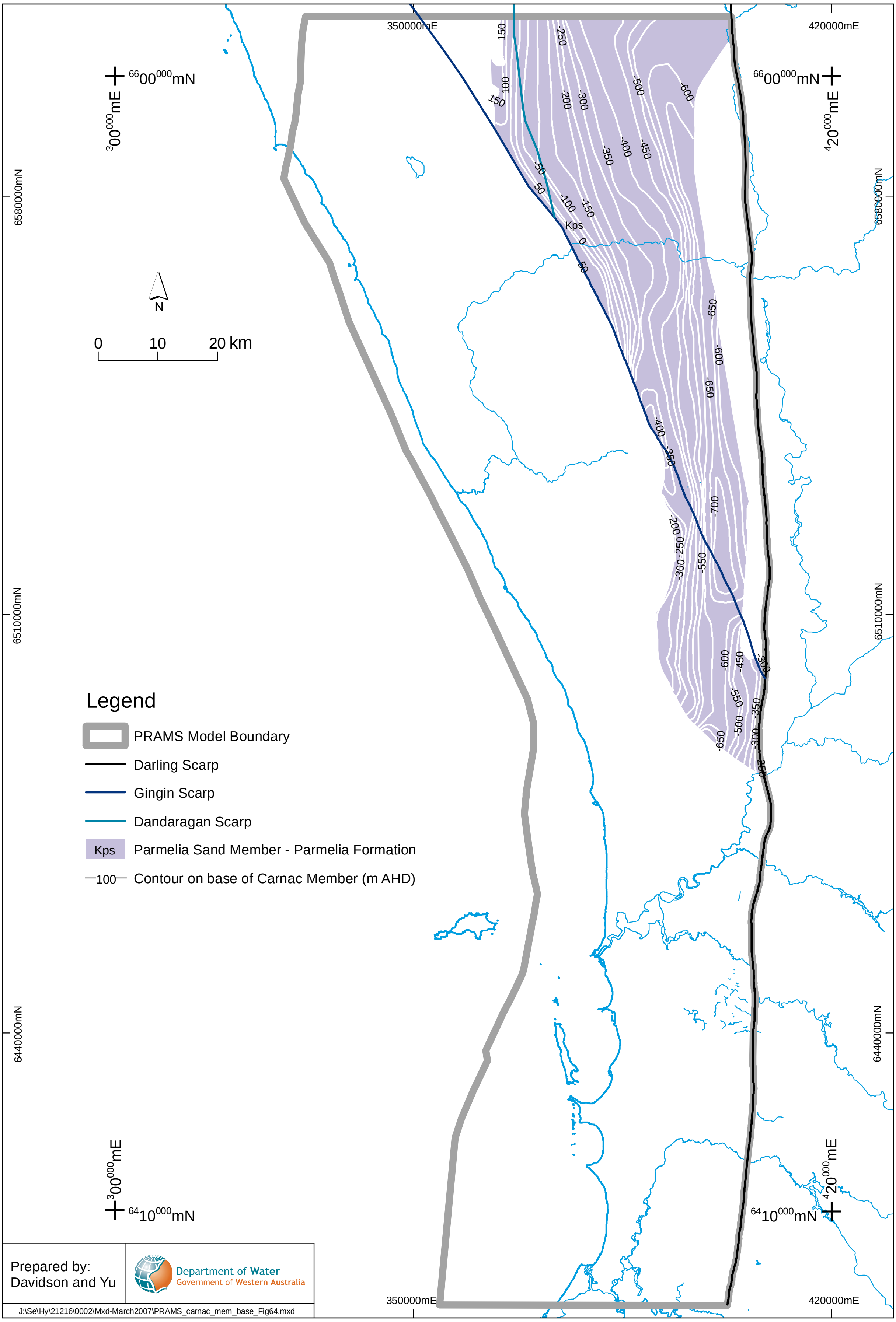


Figure 64 Carnac Member: contours on base of unit; with strata subcrop

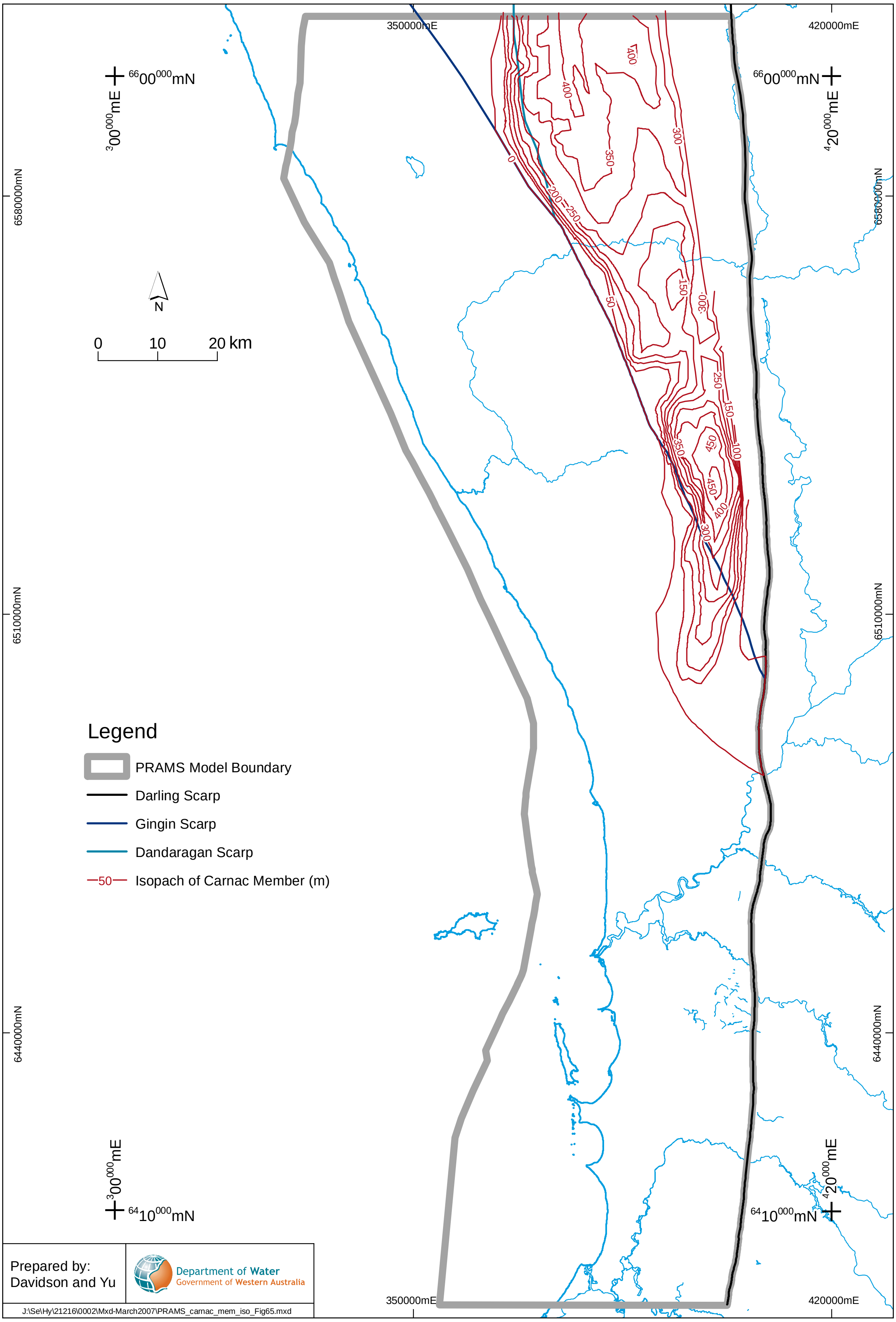


Figure 65 Carnac Member: isopachs

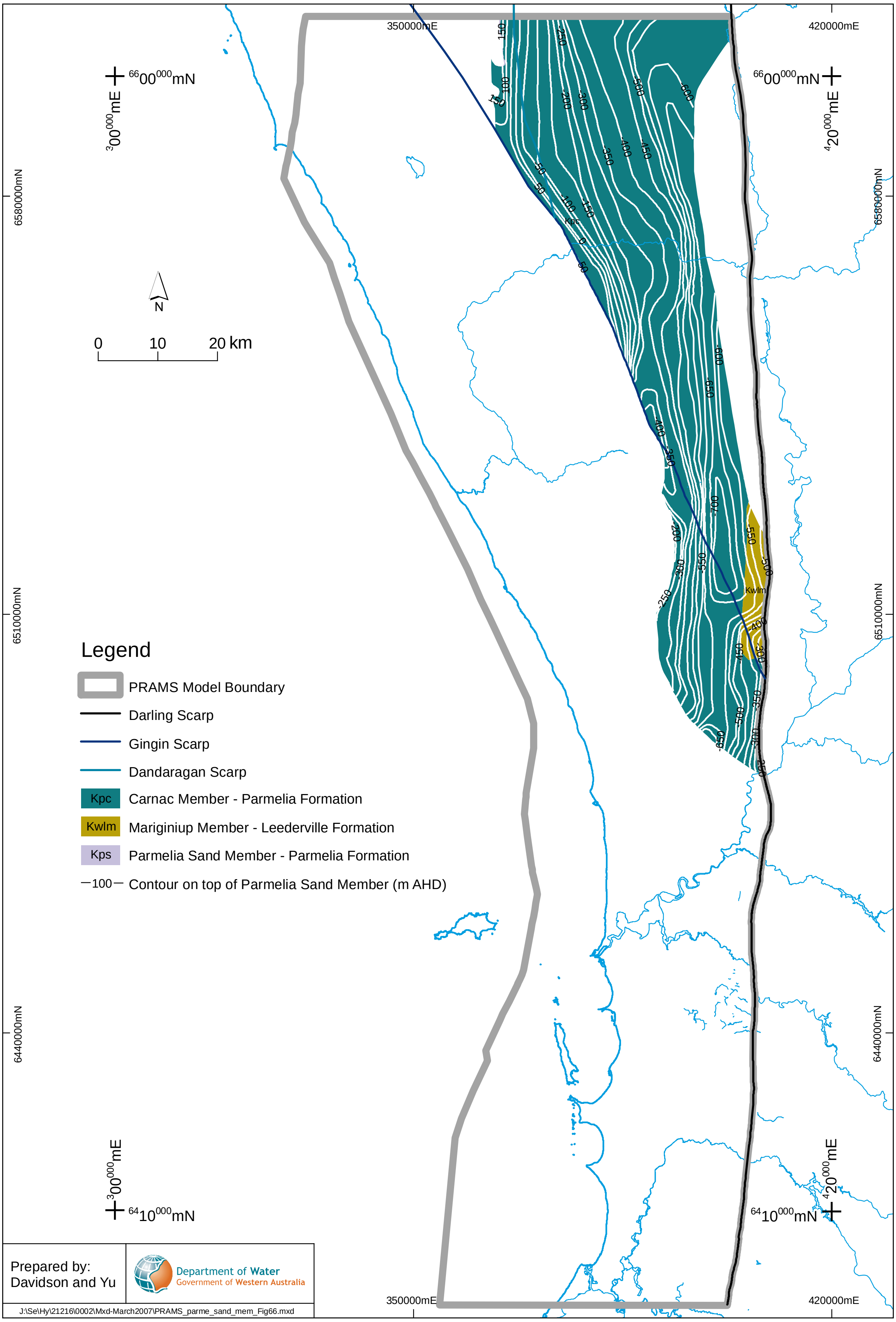


Figure 66 Parmelia Sand Member: contours on top of unit; with overlying strata

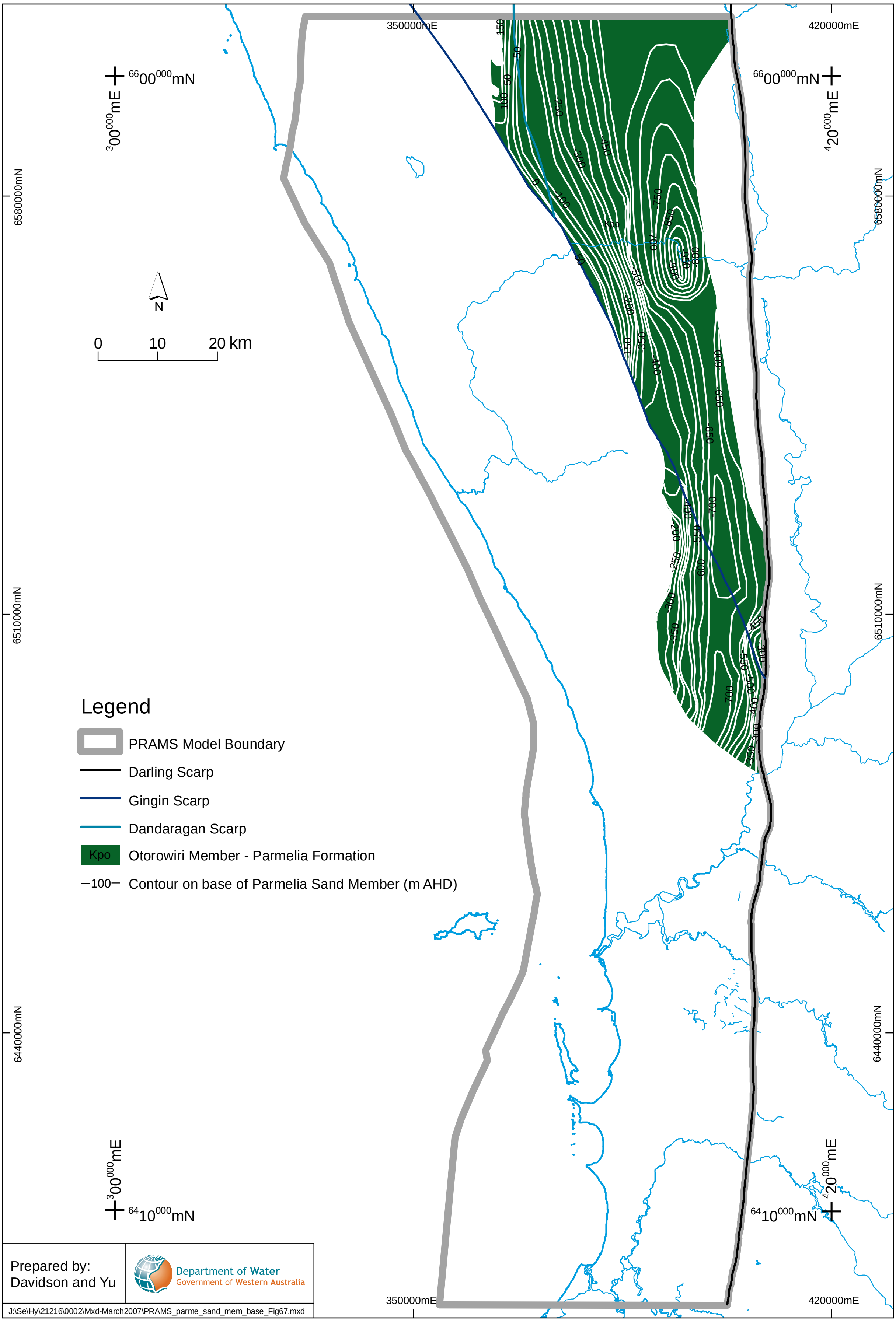


Figure 67 Parmelia Sand Member: contours on base of unit; with strata subcrop

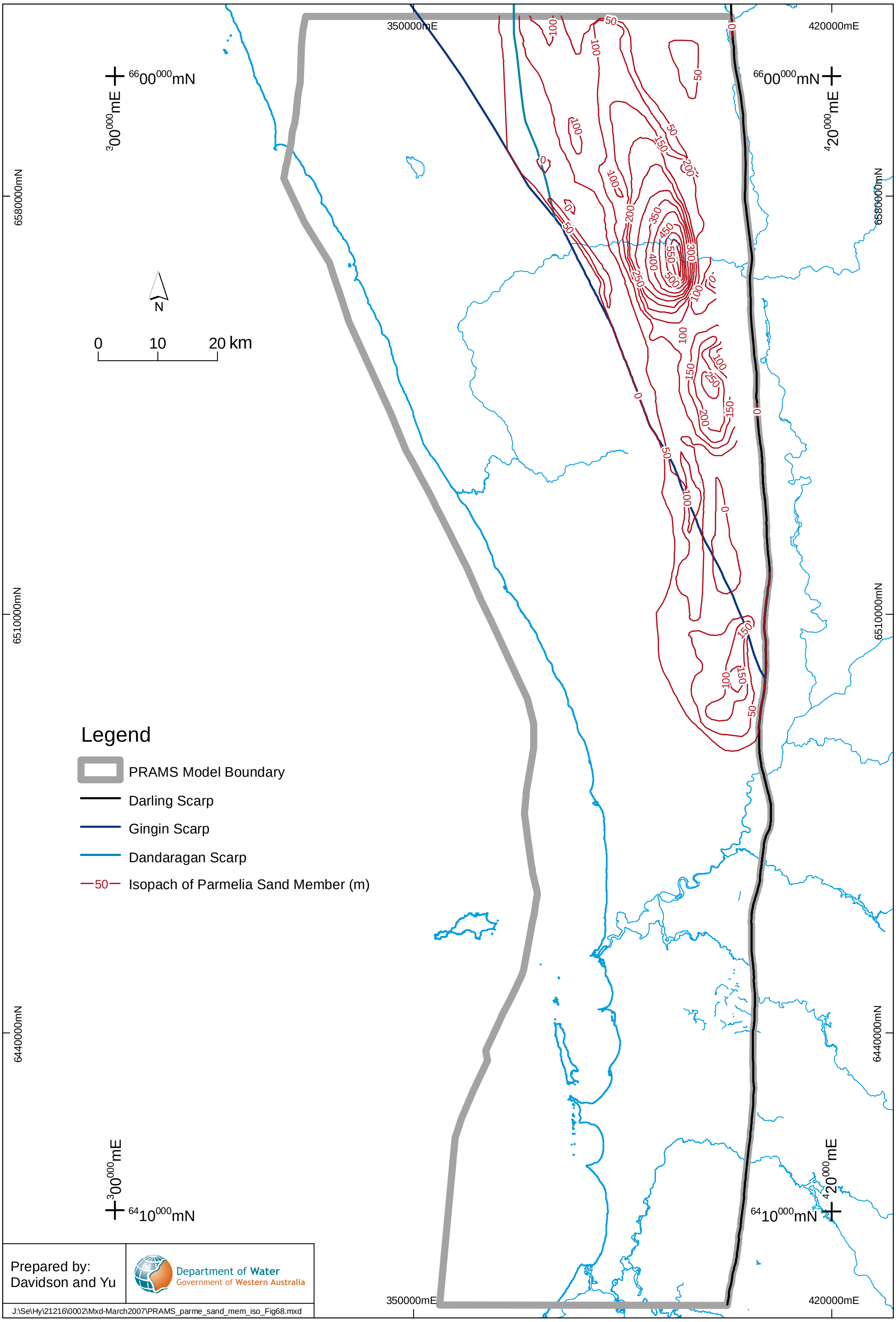


Figure 68 Parmelia Sand Member: isopachs

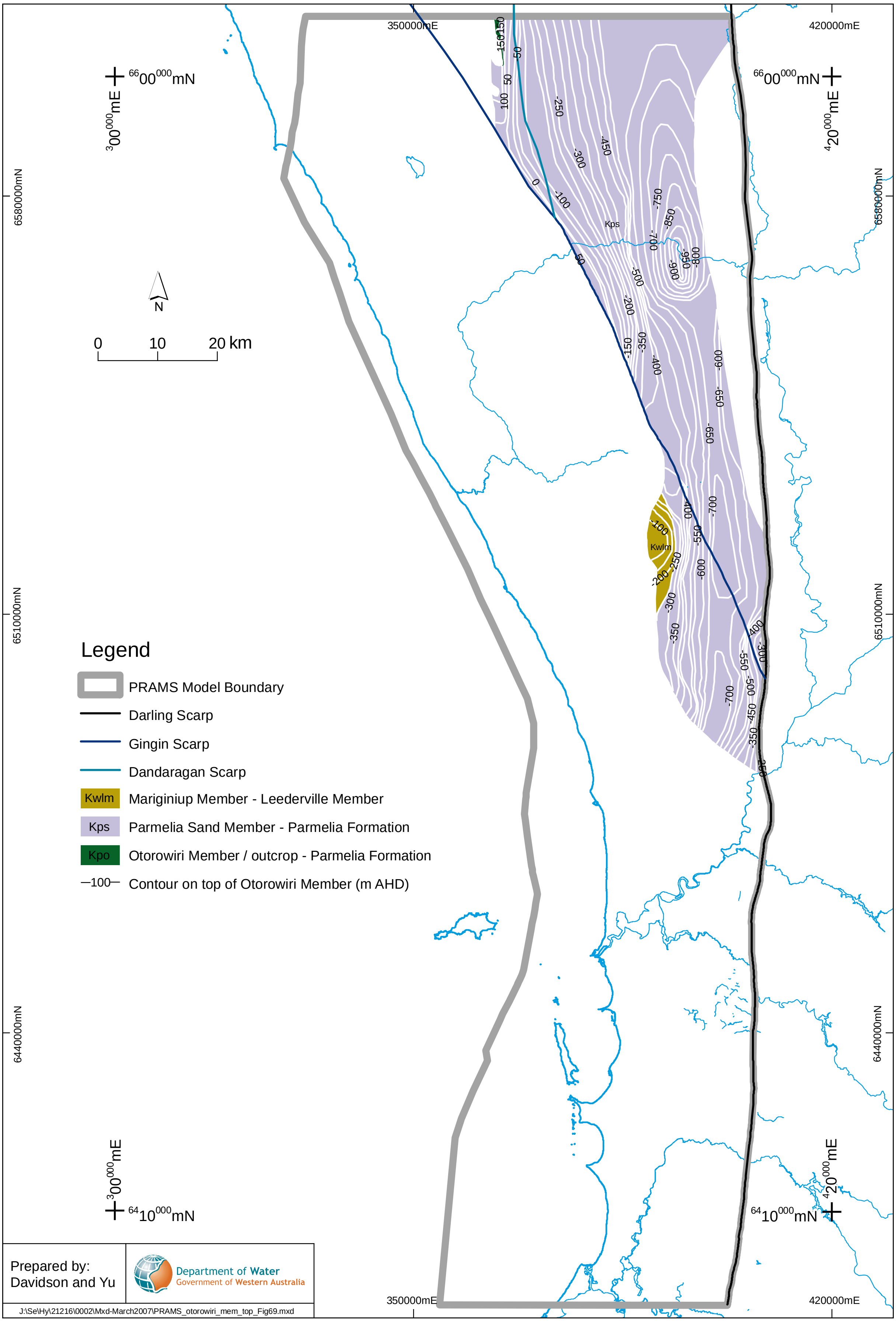


Figure 69 Otorowiri Member: contours on top of unit; with overlying strata

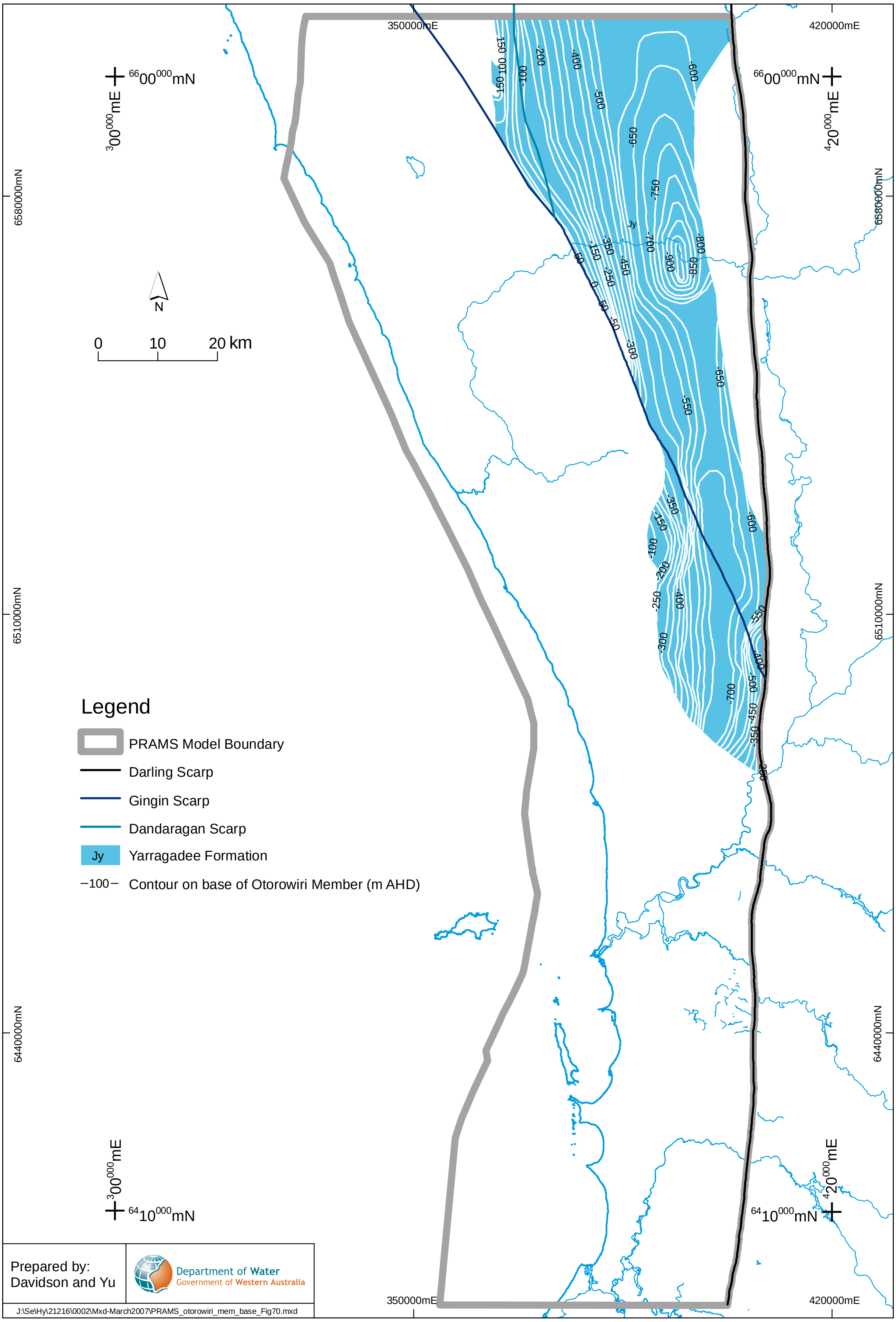


Figure 70 Otorowiri Member: contours on base of unit; with strata subcrop

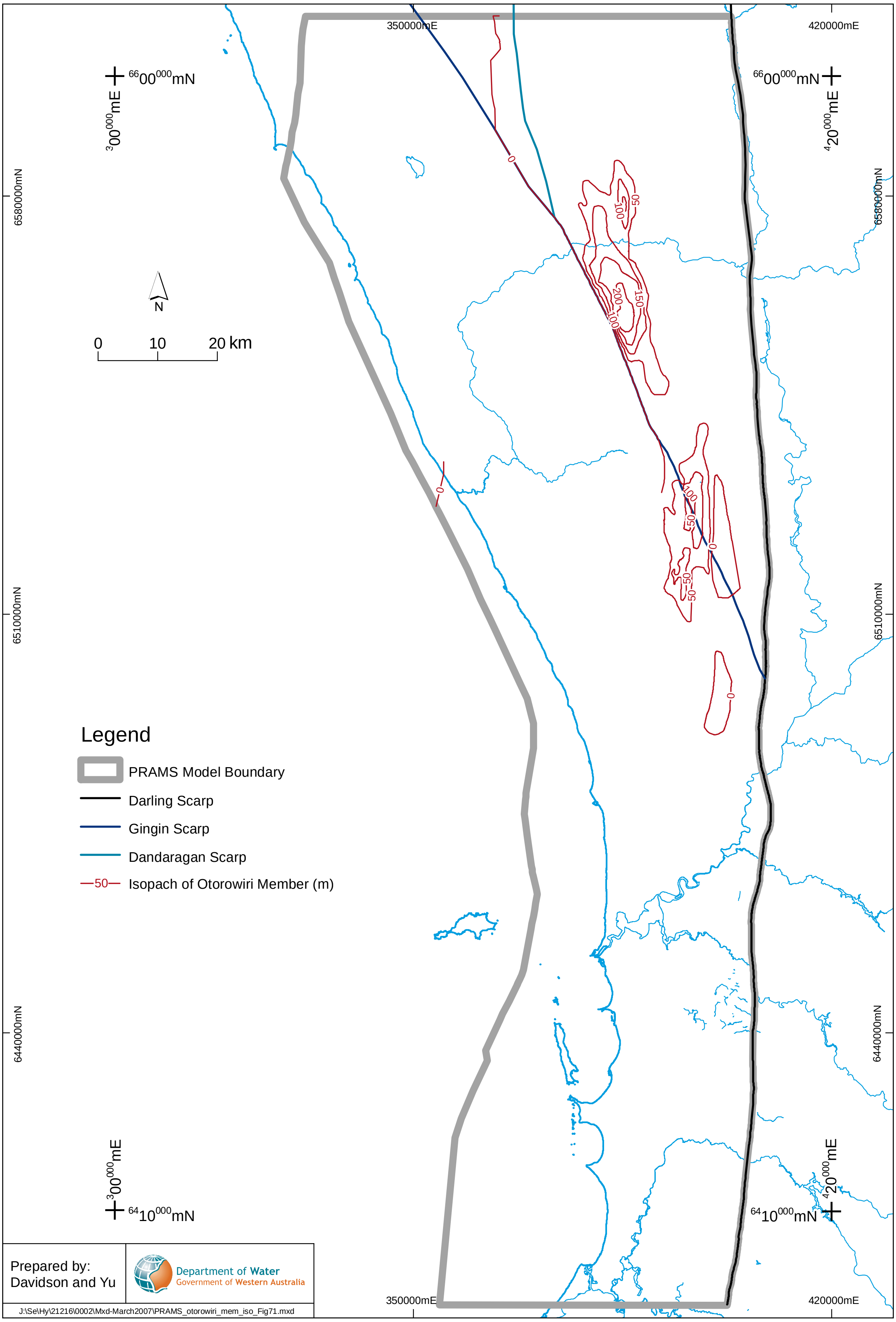


Figure 71 Otorowiri Member: isopachs

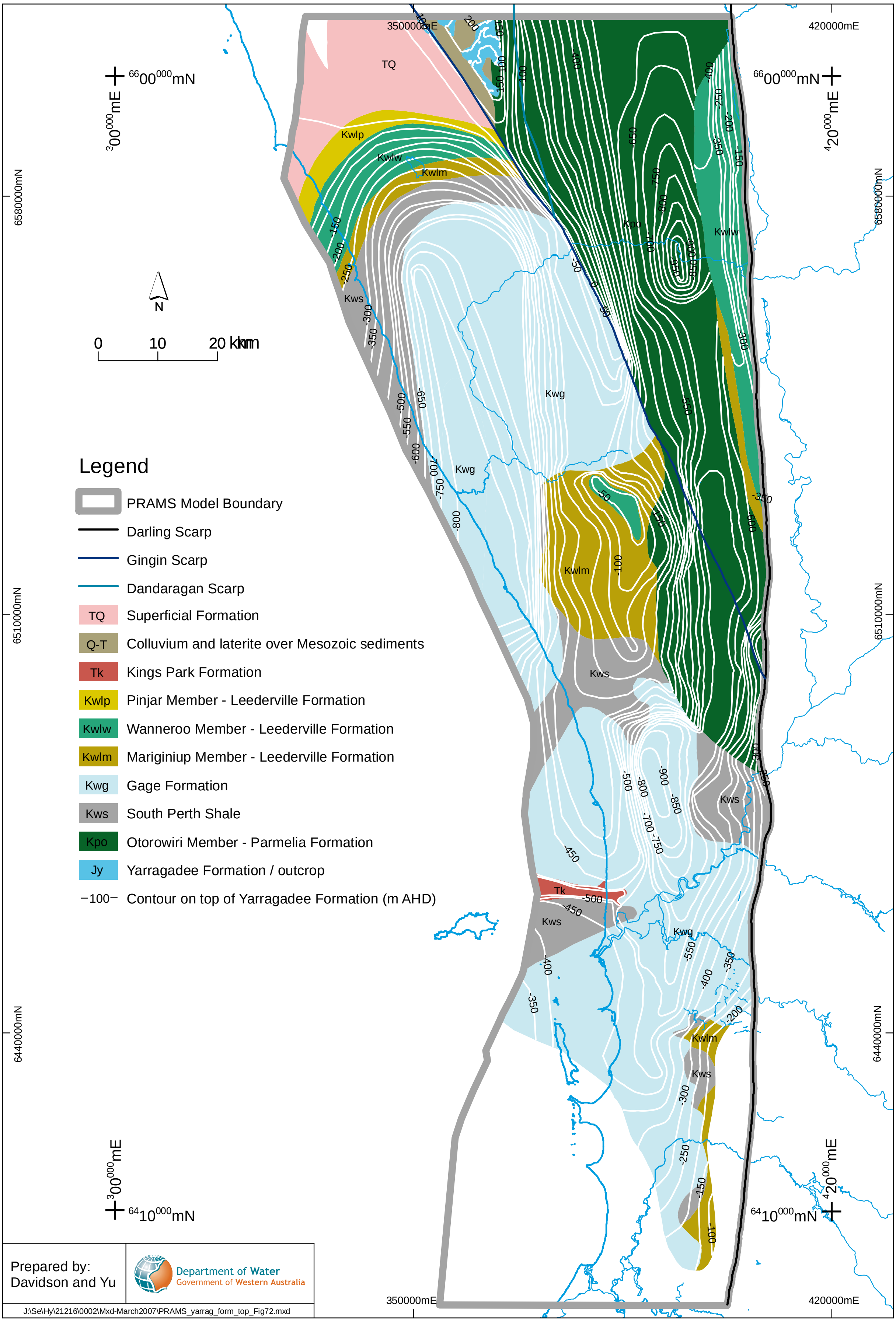


Figure 72 Yarragadee Formation: contours on top of unit; with overlying strata

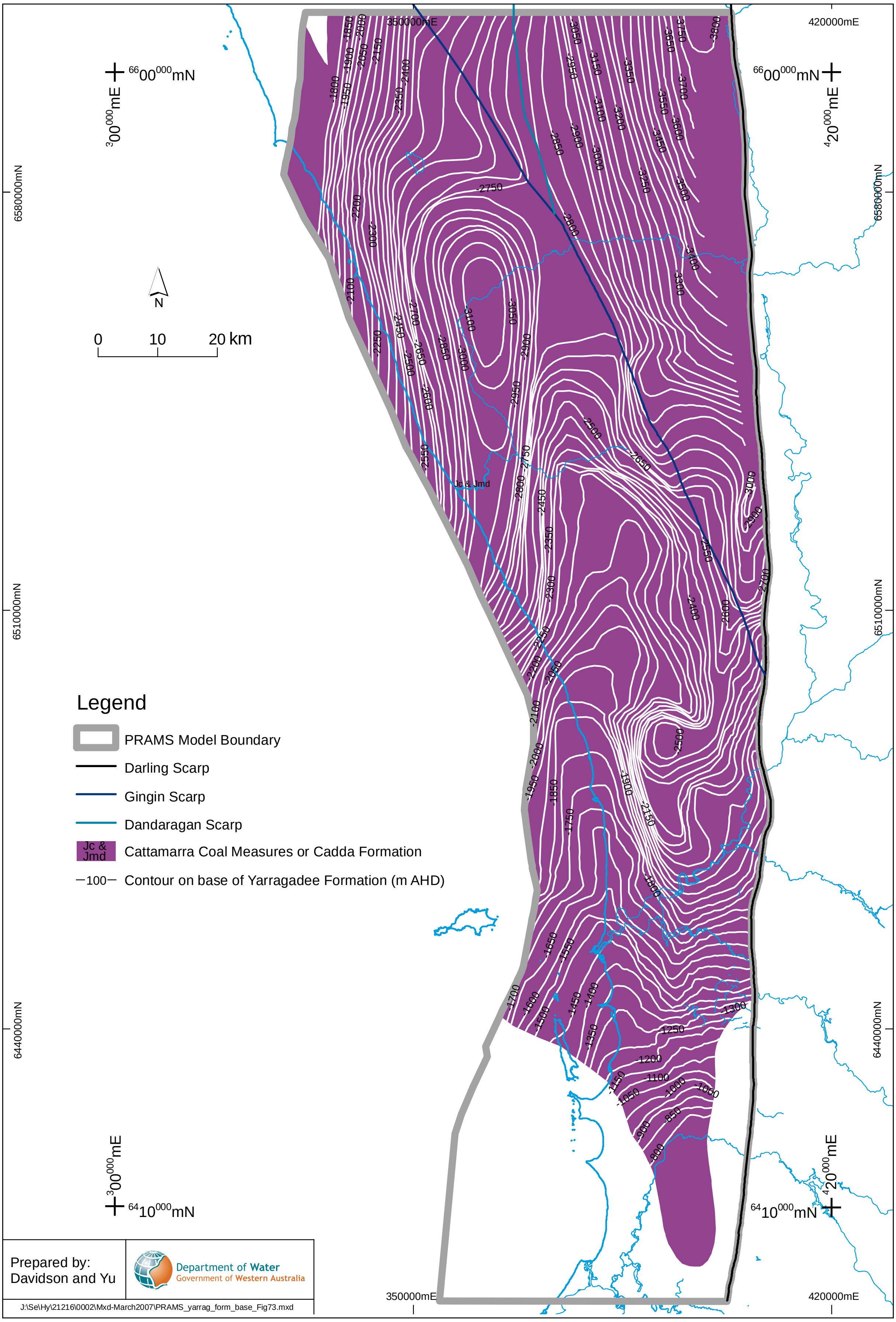


Figure 73 Yarragadee Formation: contours on base of unit; with strata subcrop

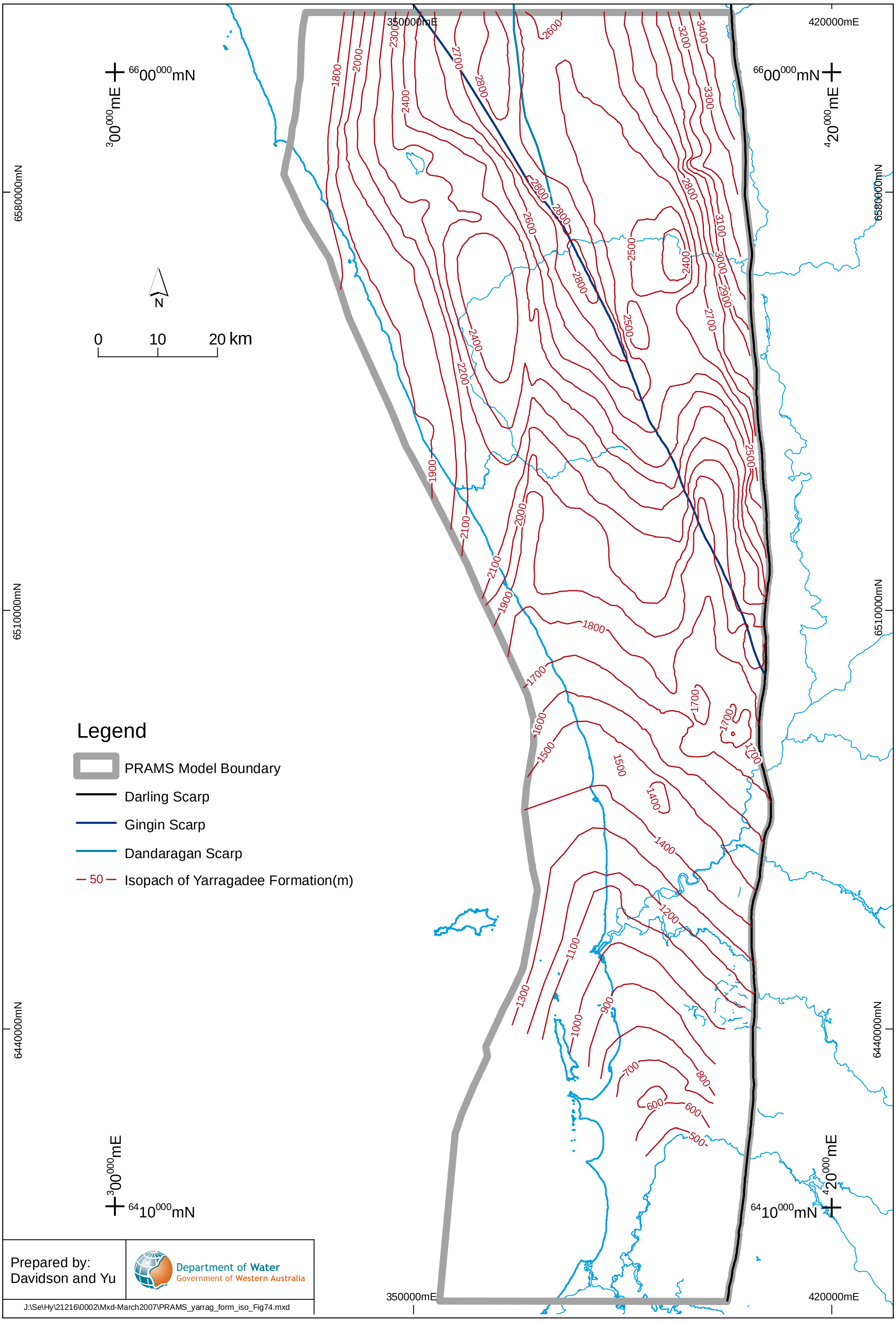


Figure 74 Yarragadee Formation: isopachs

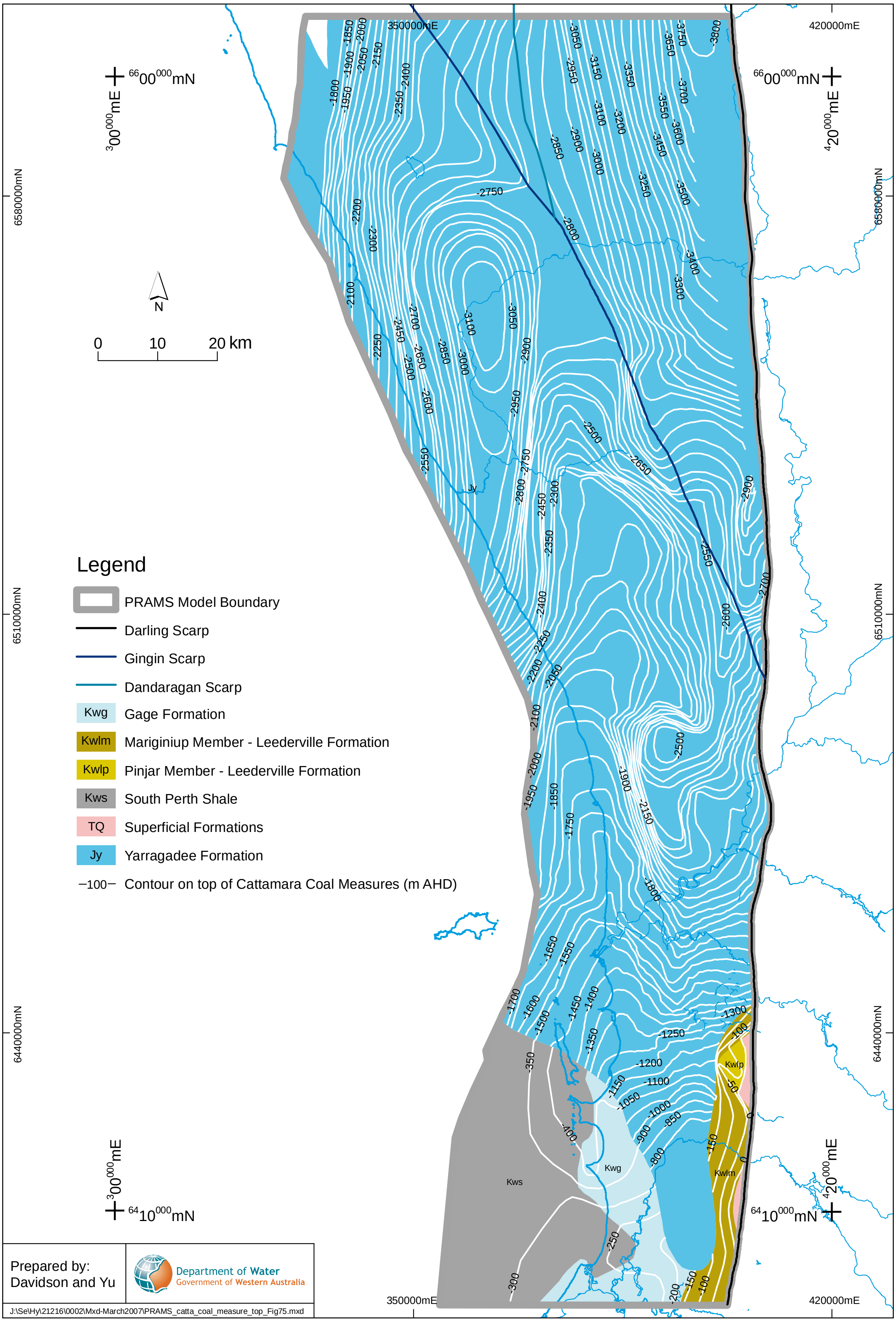


Figure 75 Cattamarra Coal Measures: contours on top of unit; with overlying strata

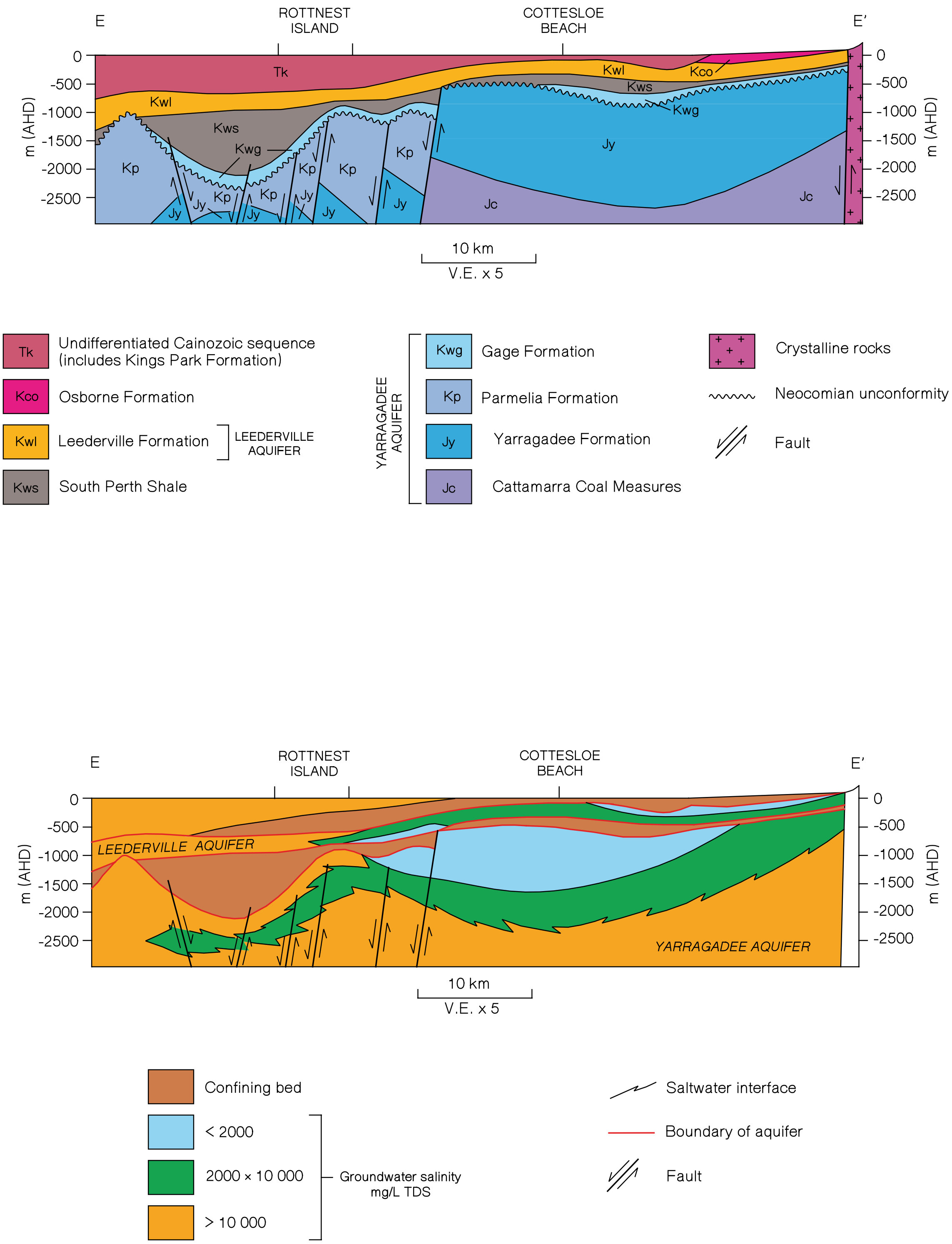


Figure 76 Confined aquifers: schematic section of groundwater/oceanwater interface

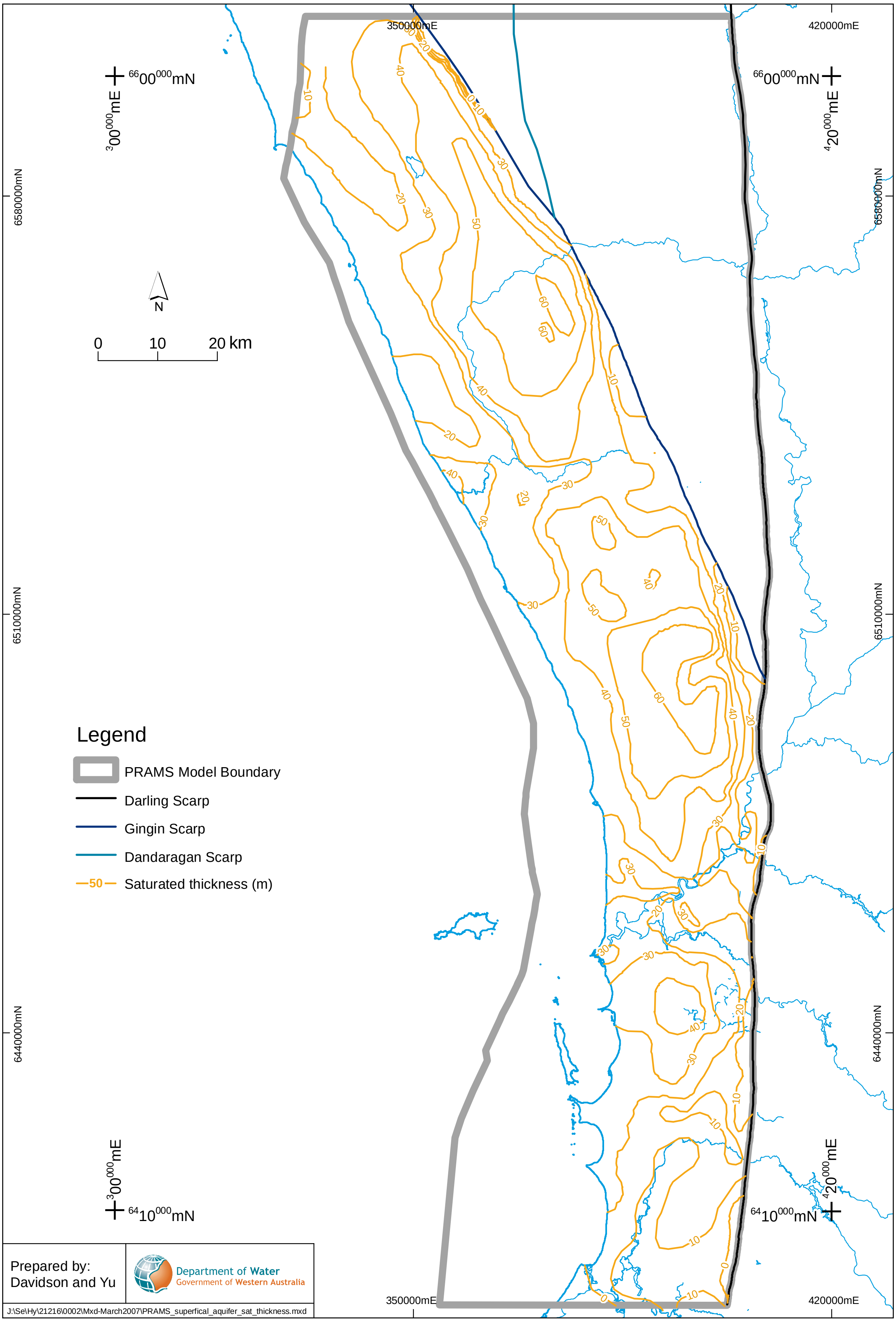


Figure 77 Superficial aquifer: saturated thickness April 2003

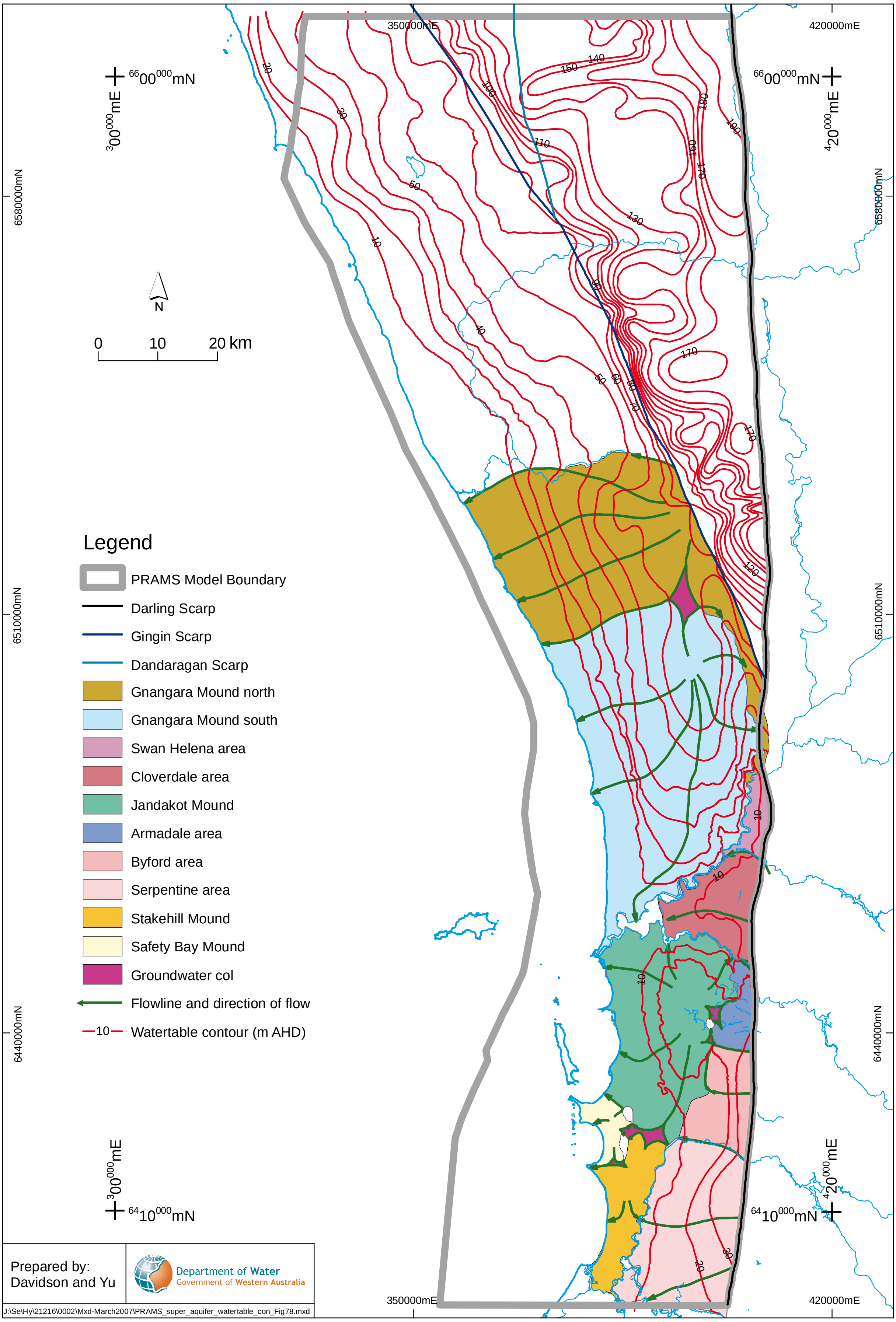


Figure 78 Superficial aquifer: watertable contours April 2003

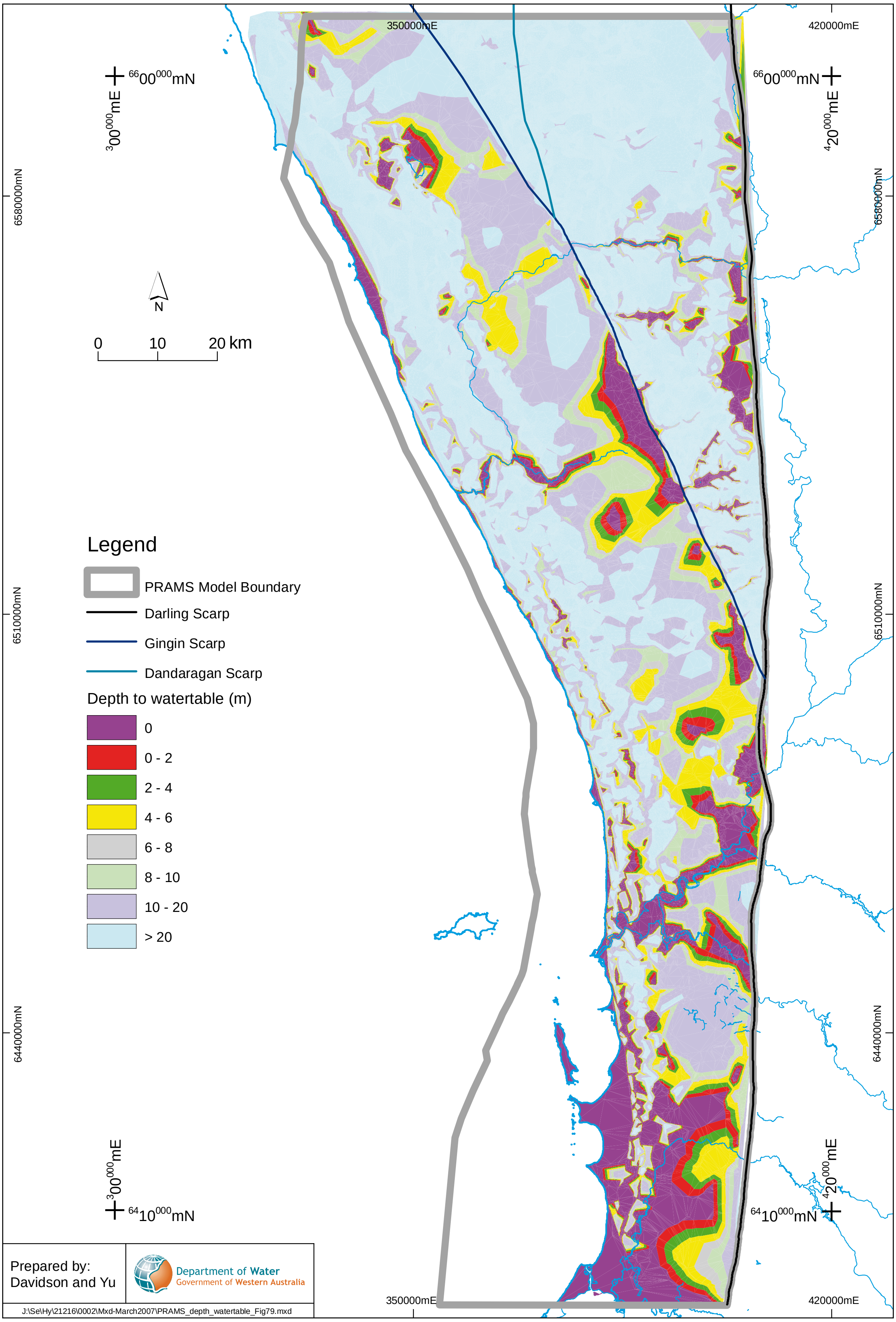


Figure 79 Superficial aquifer: depth to the watertable April 2003

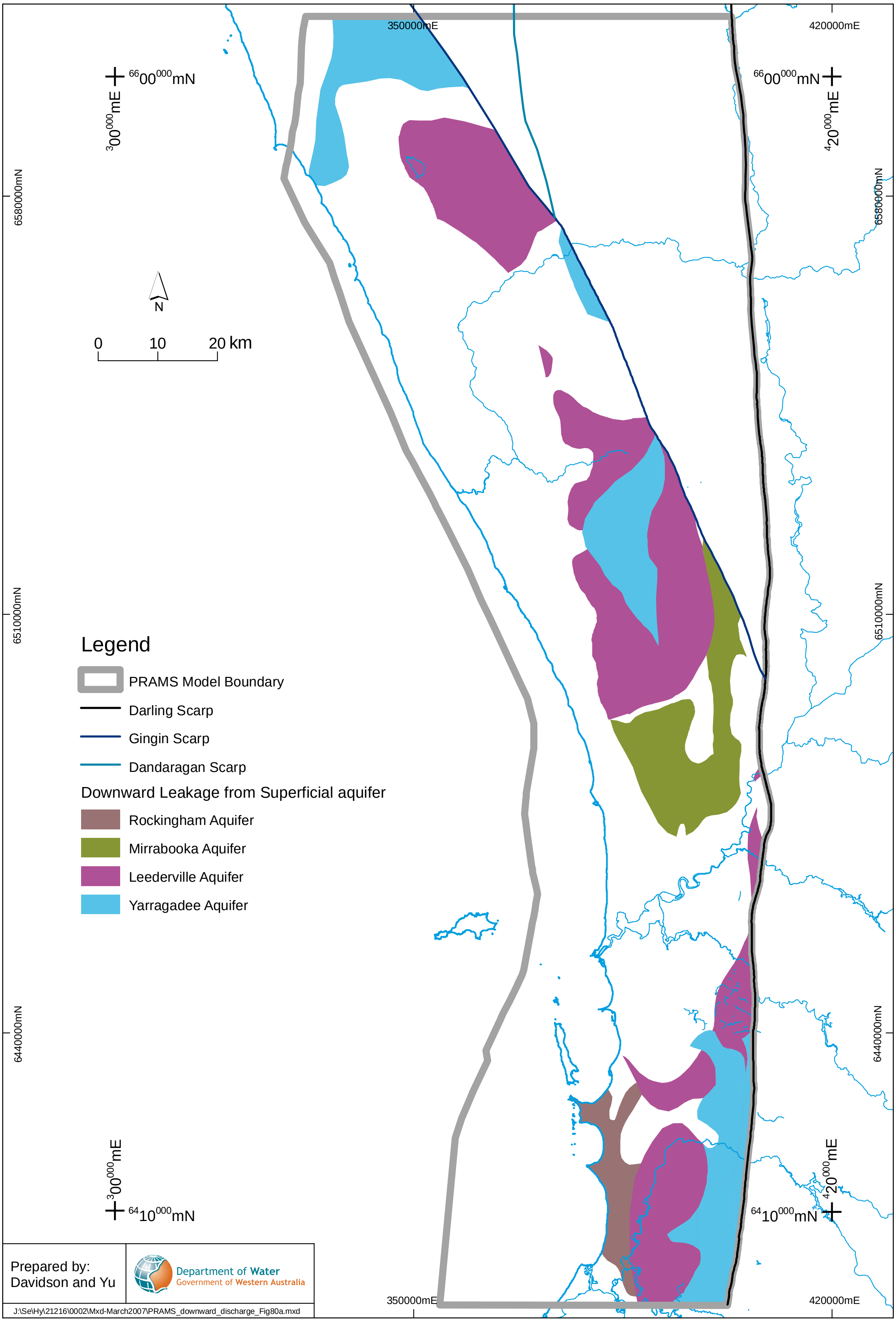


Figure 80a Superficial aquifer: areas of downward discharge to aquifer

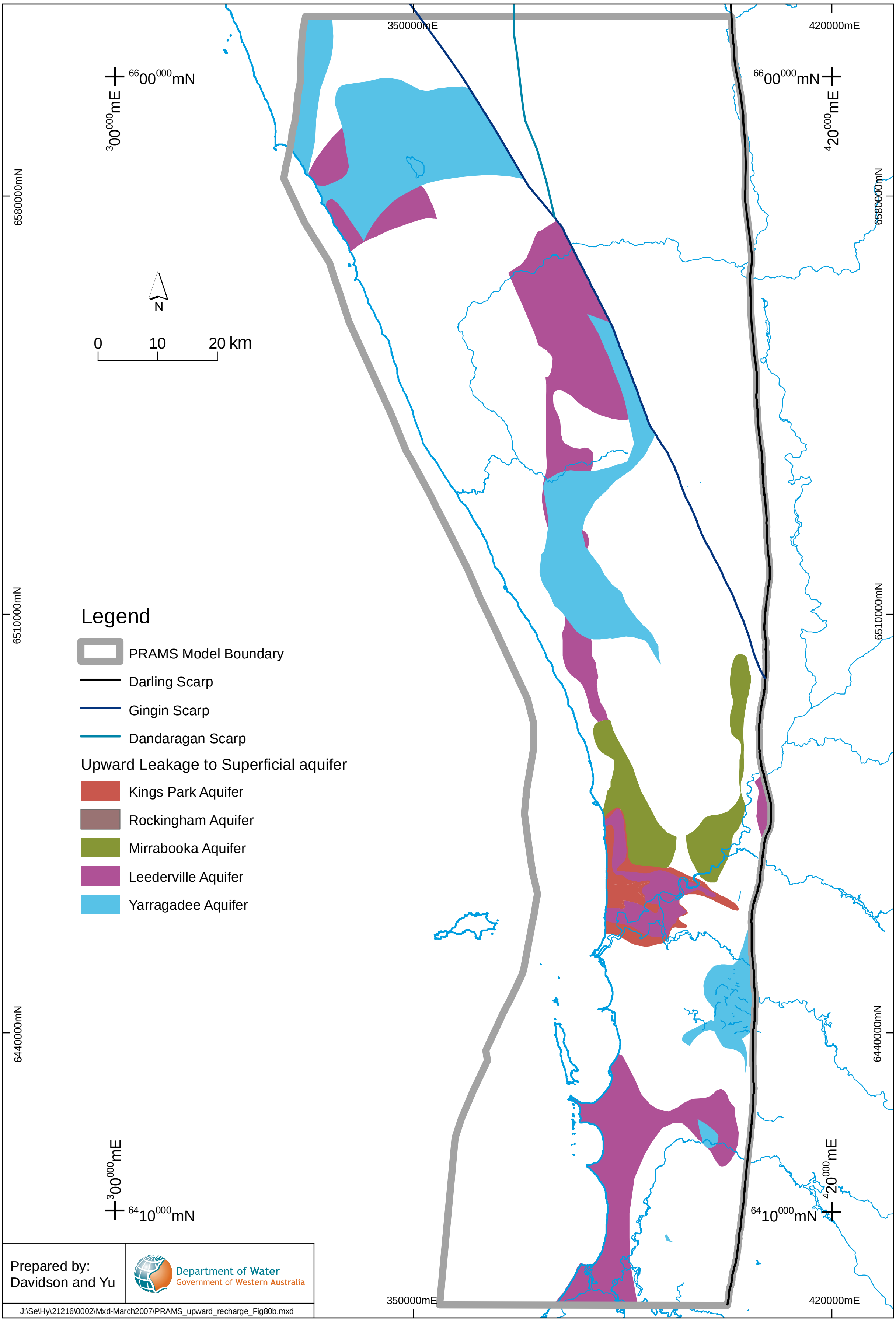


Figure 80b Superficial aquifer: areas of upward recharge from aquifer

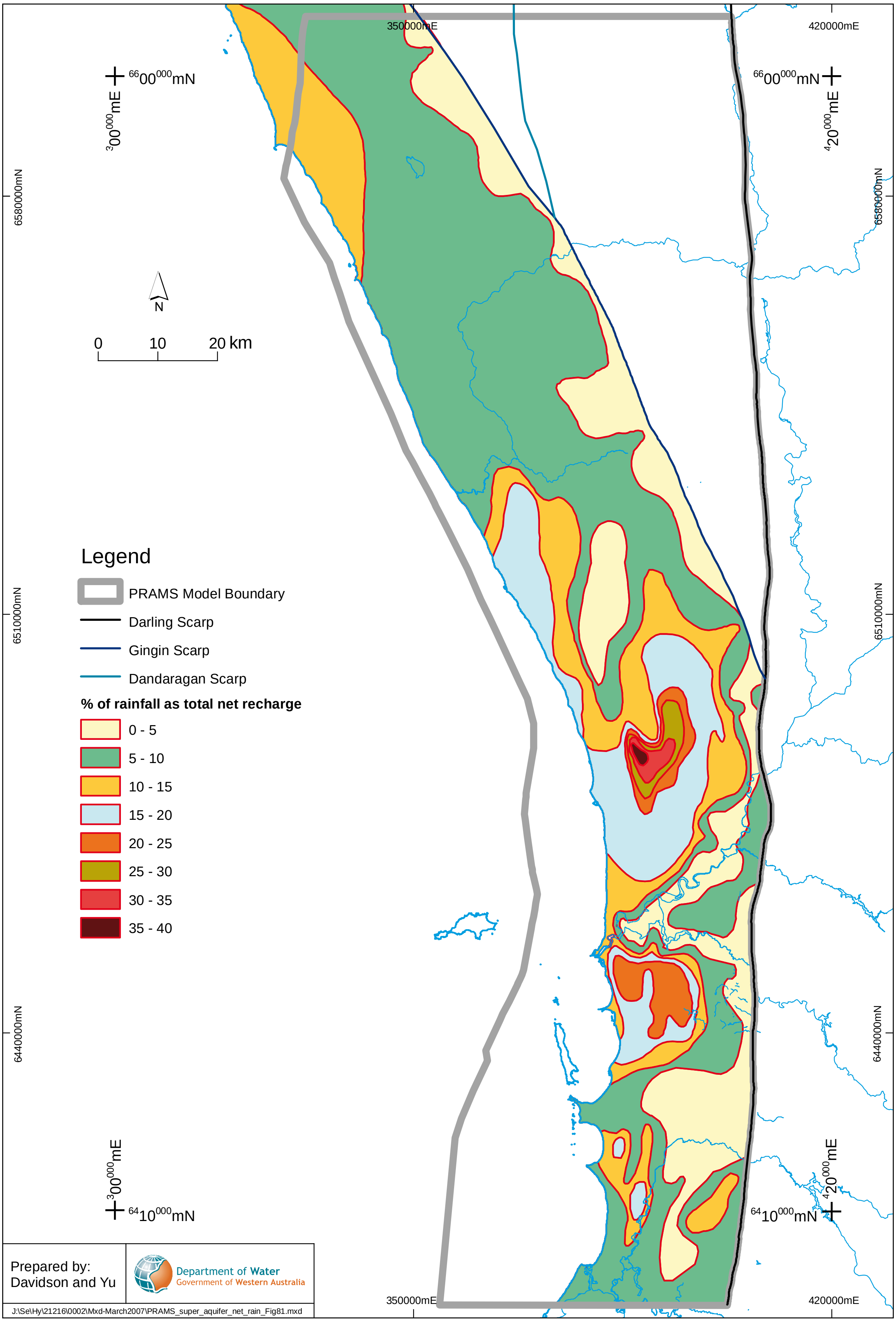


Figure 81 Superficial aquifer: percentage of net rainfall recharge

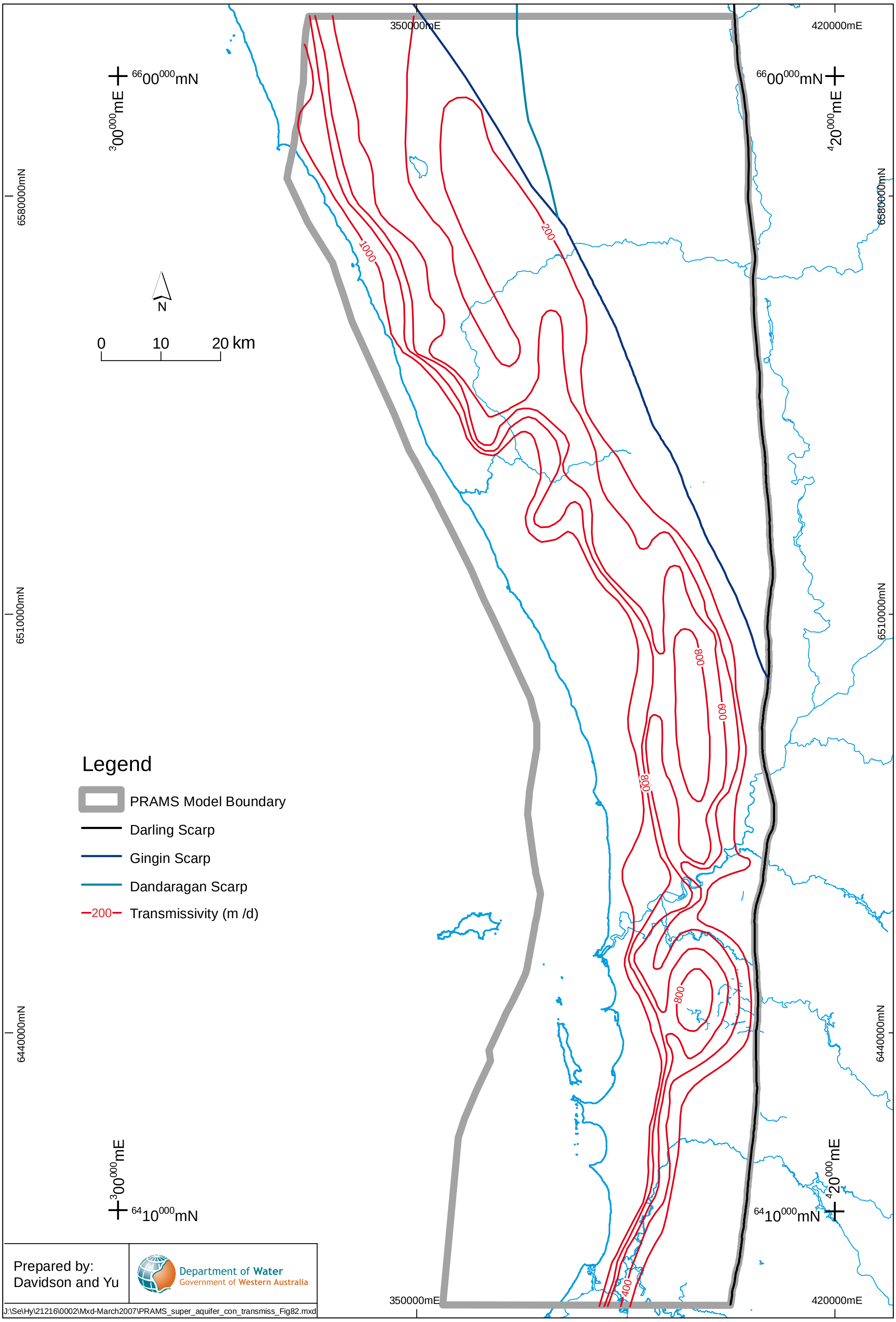


Figure 82 Superficial aquifer: contours of transmissivity April 2003

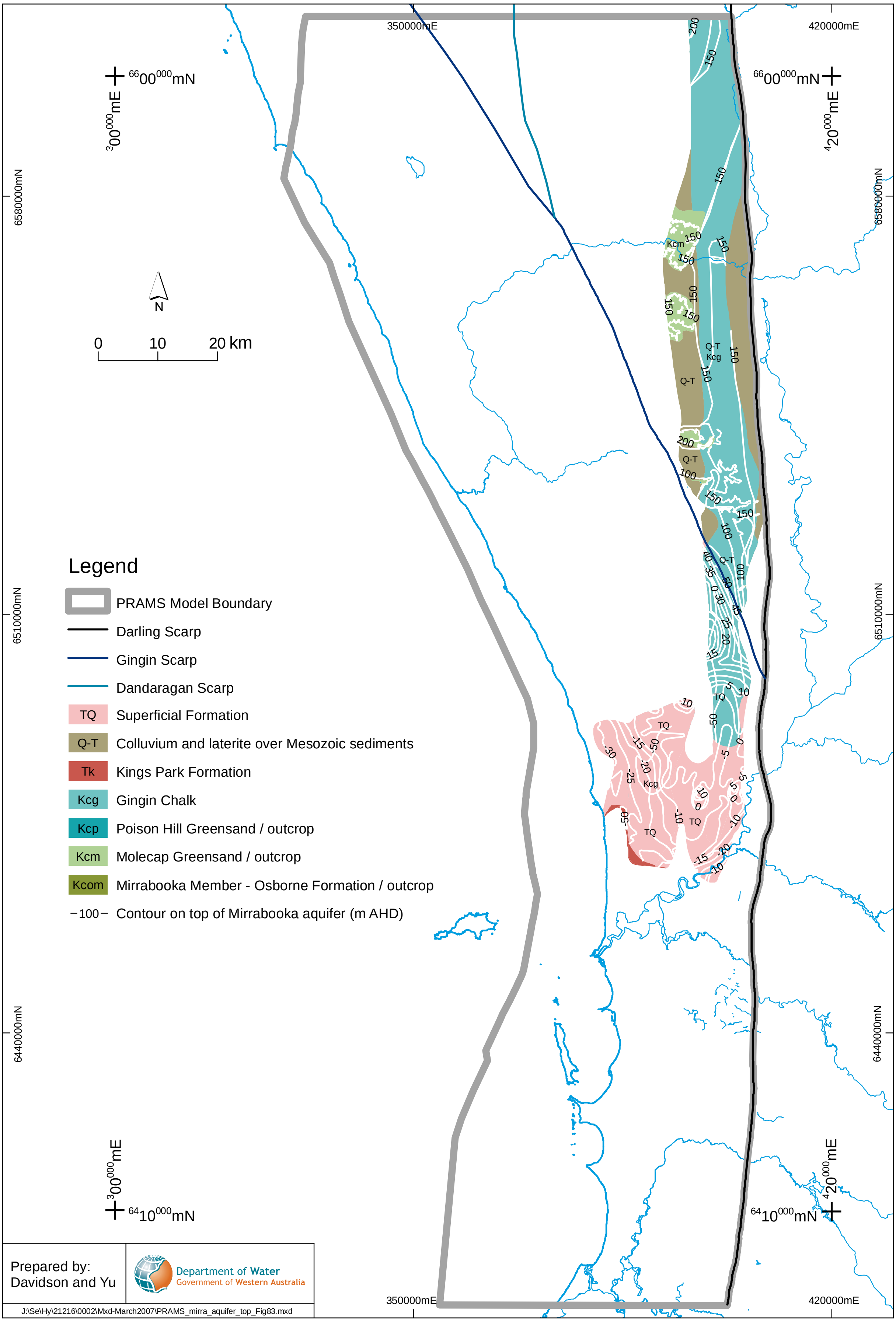


Figure 83 Mirrabooka aquifer: contours on top of aquifer; with overlying strata

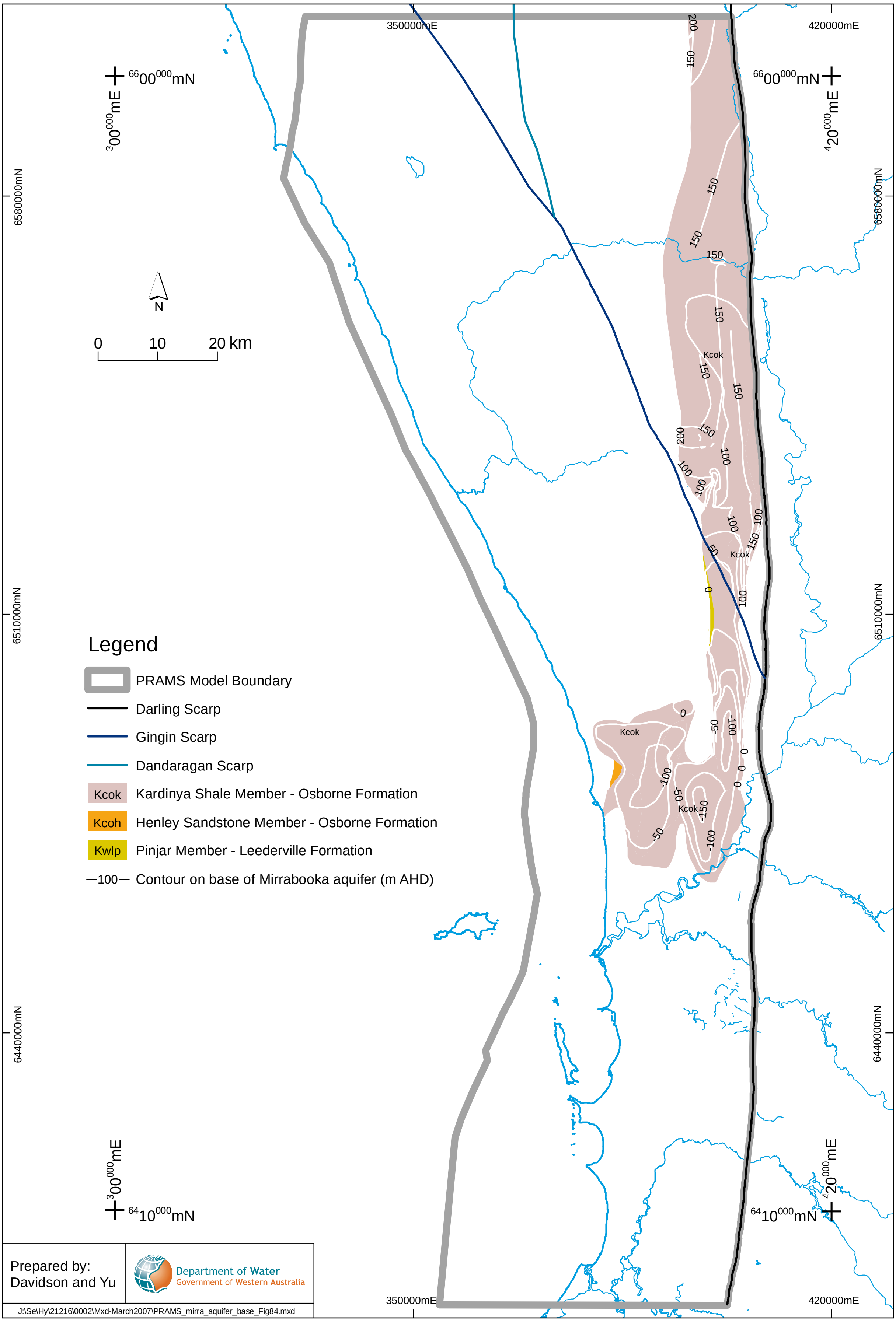


Figure 84 Mirrabooka aquifer: contours on base of aquifer; with strata subcrop

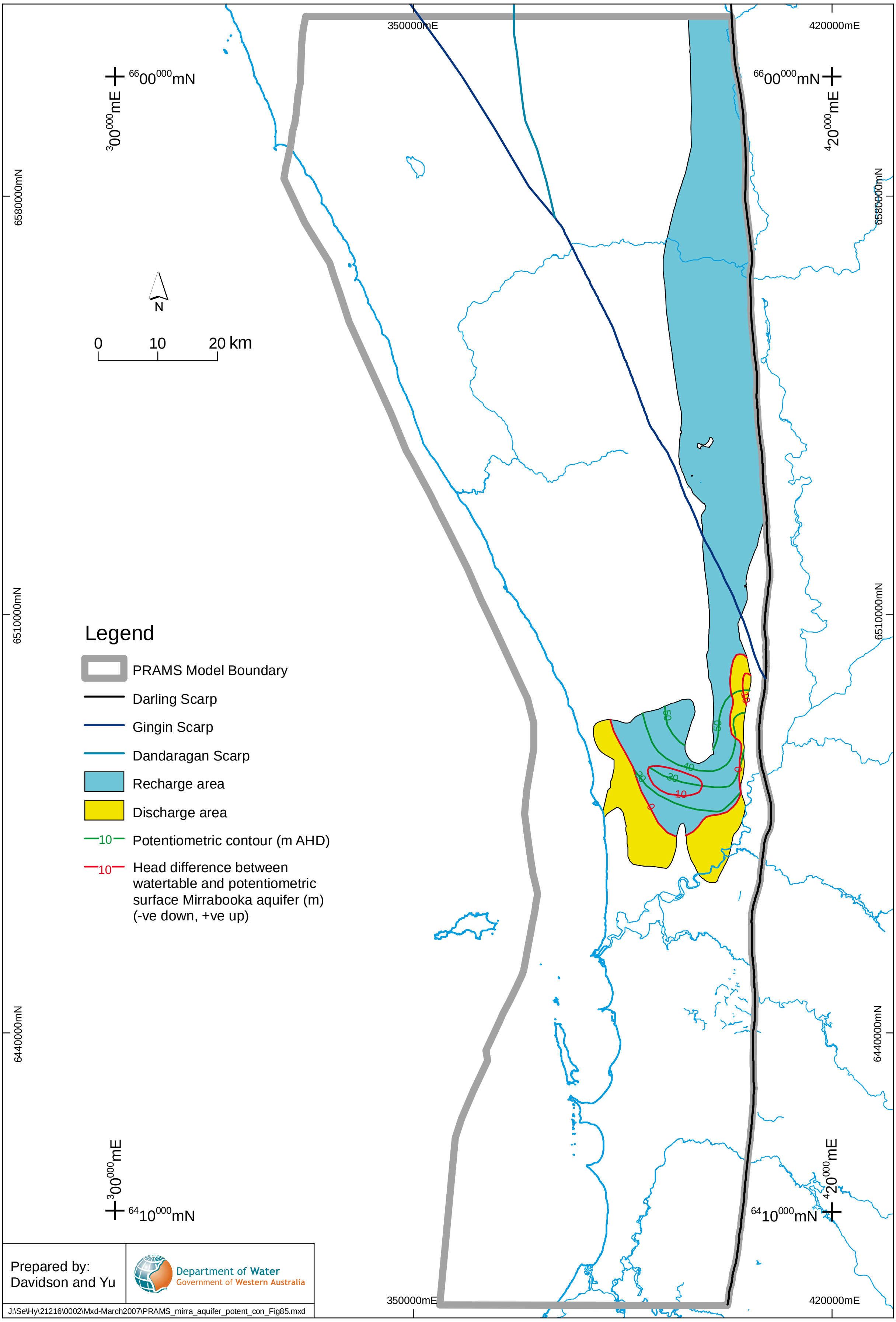


Figure 85 Mirrabooka aquifer: potentiometric contours

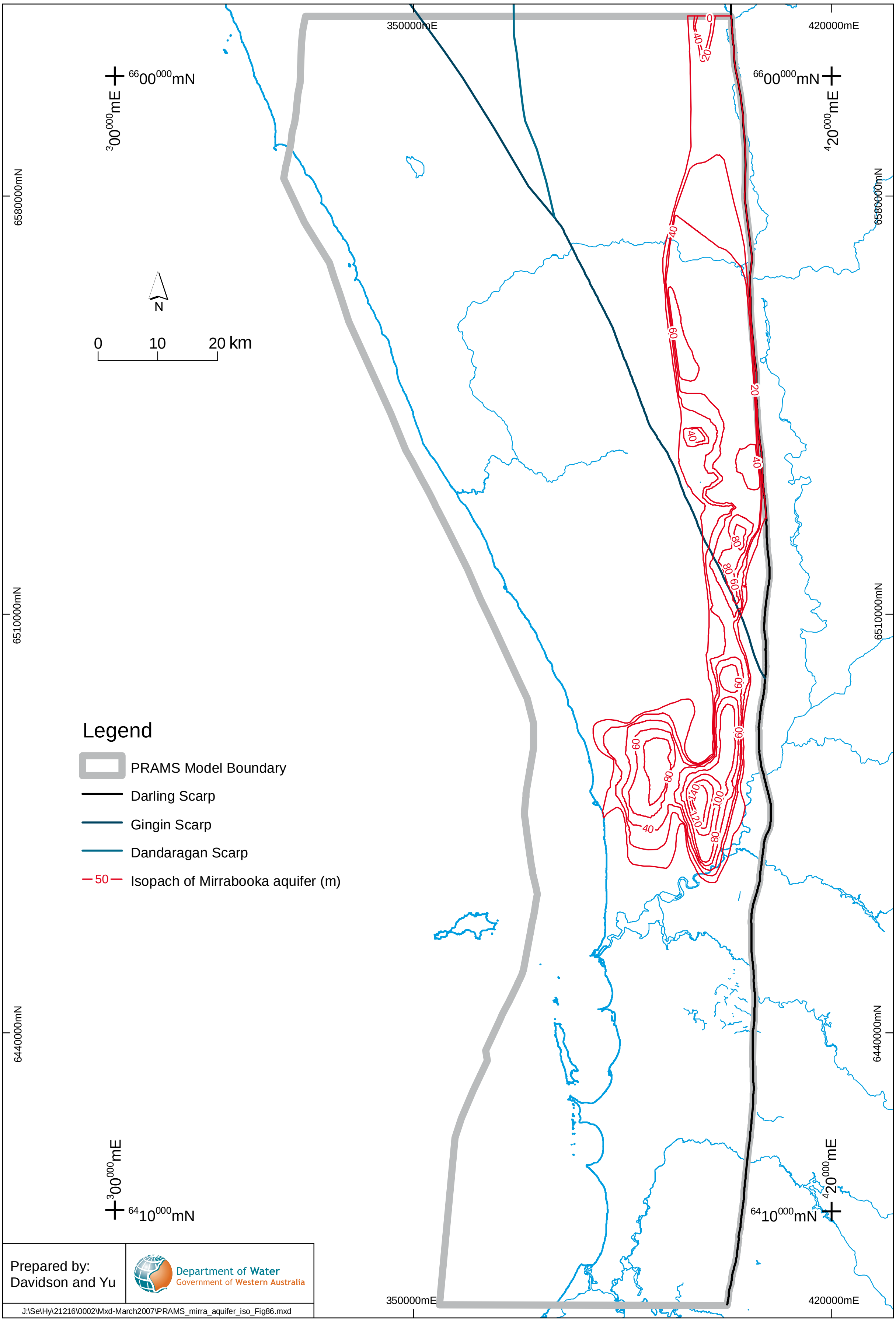


Figure 86 Mirrabooka aquifer: isopachs

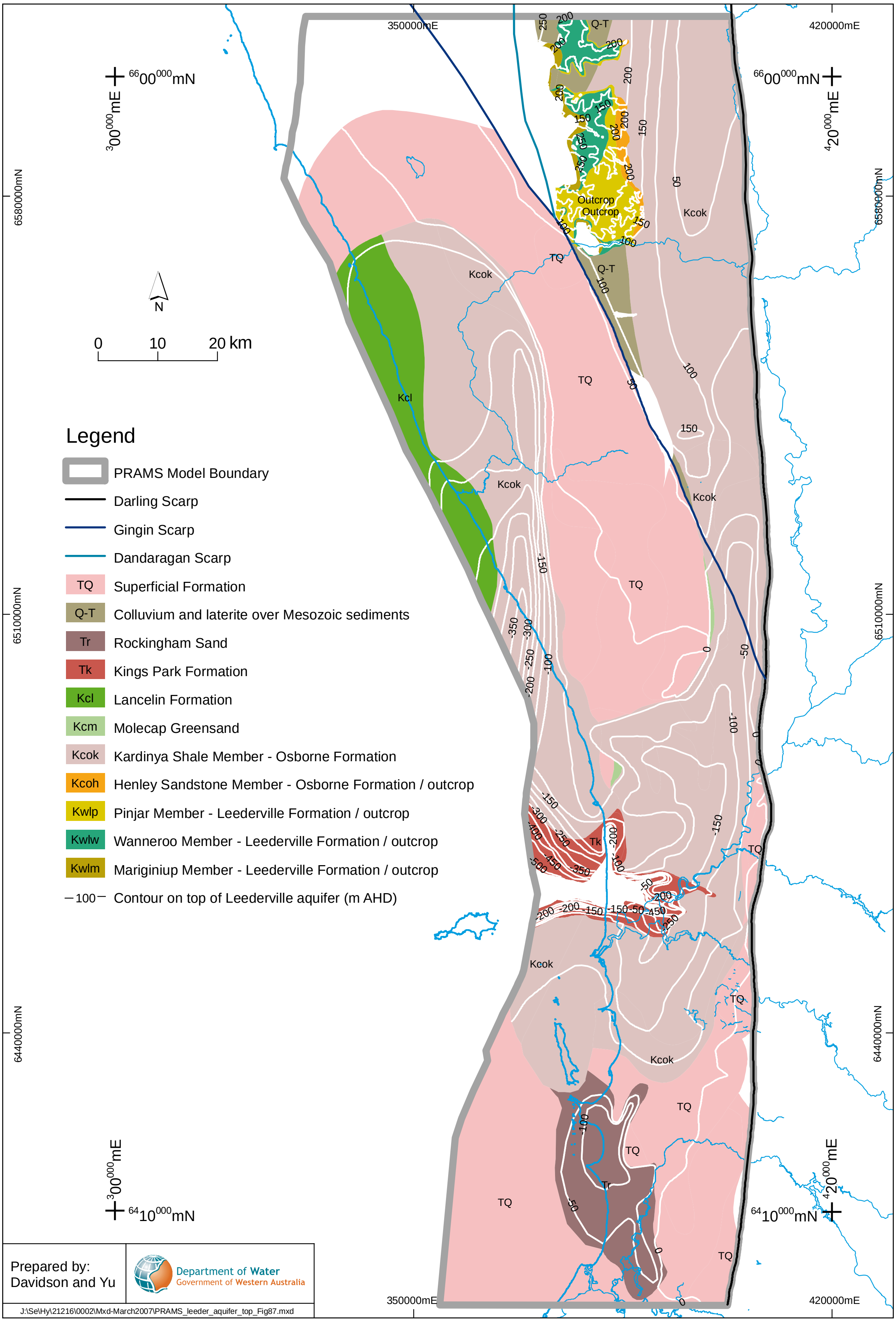


Figure 87 Leederville aquifer: contours on top of aquifer; with overlying strata

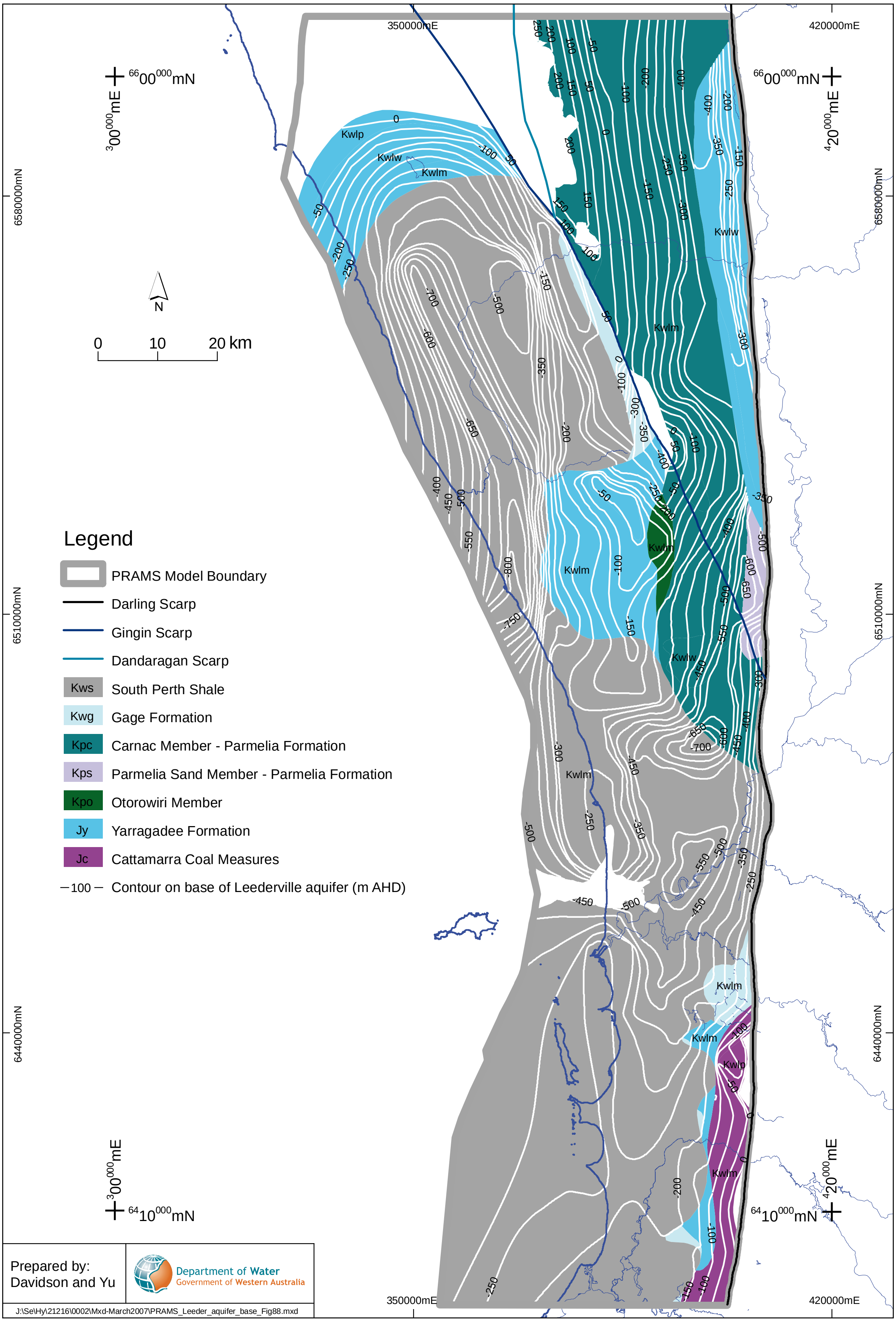


Figure 88 Leederville aquifer: contours on base of aquifer; with strata subcrop

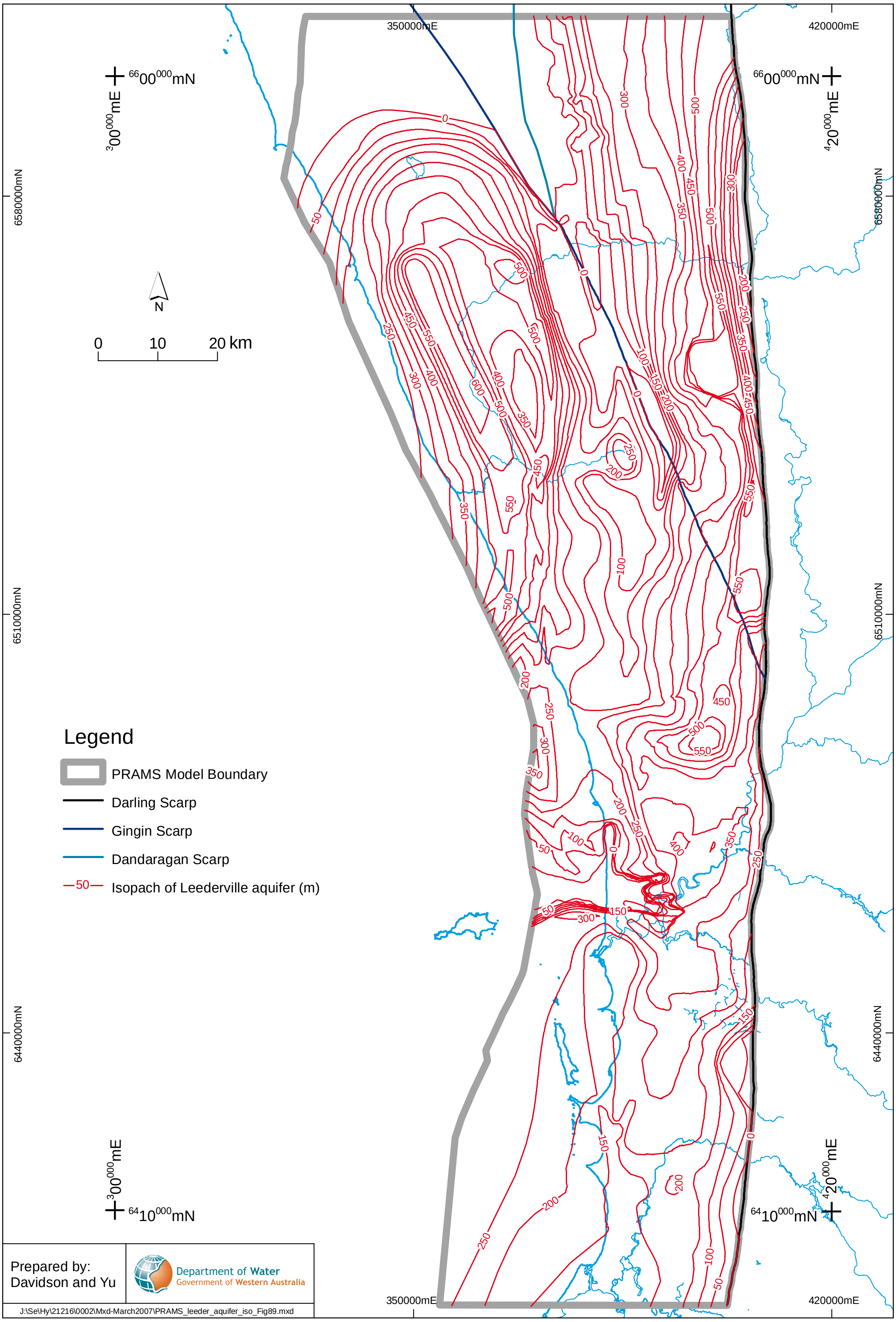
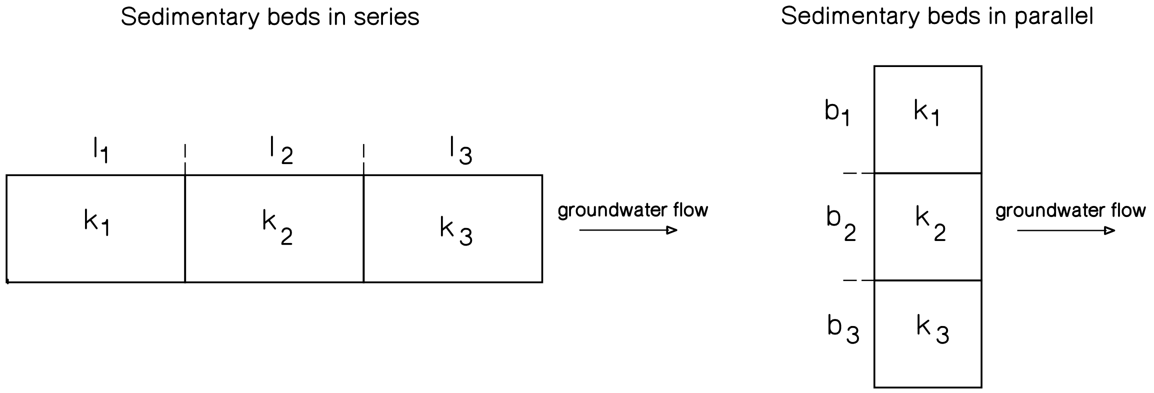


Figure 89 Leederville aquifer: isopachs



Harmonic mean if the sedimentary beds are in series:

$$\frac{\Sigma l_1}{k \text{ mean}} = \Sigma \frac{l_1}{k_1} \quad (11)$$

Arithmetic mean if the sedimentary beds are in parallel:

$$k \text{ mean } \Sigma b_1 = \Sigma b_1 k_1 \quad (12)$$

where k = horizontal hydraulic conductivity (m/d)
l = length of sedimentary bed in flow direciton (m)
b = thickness of sedimentary bed (m)

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Figure 90 Horizontal hydraulic conductivities of multilayered aquifers

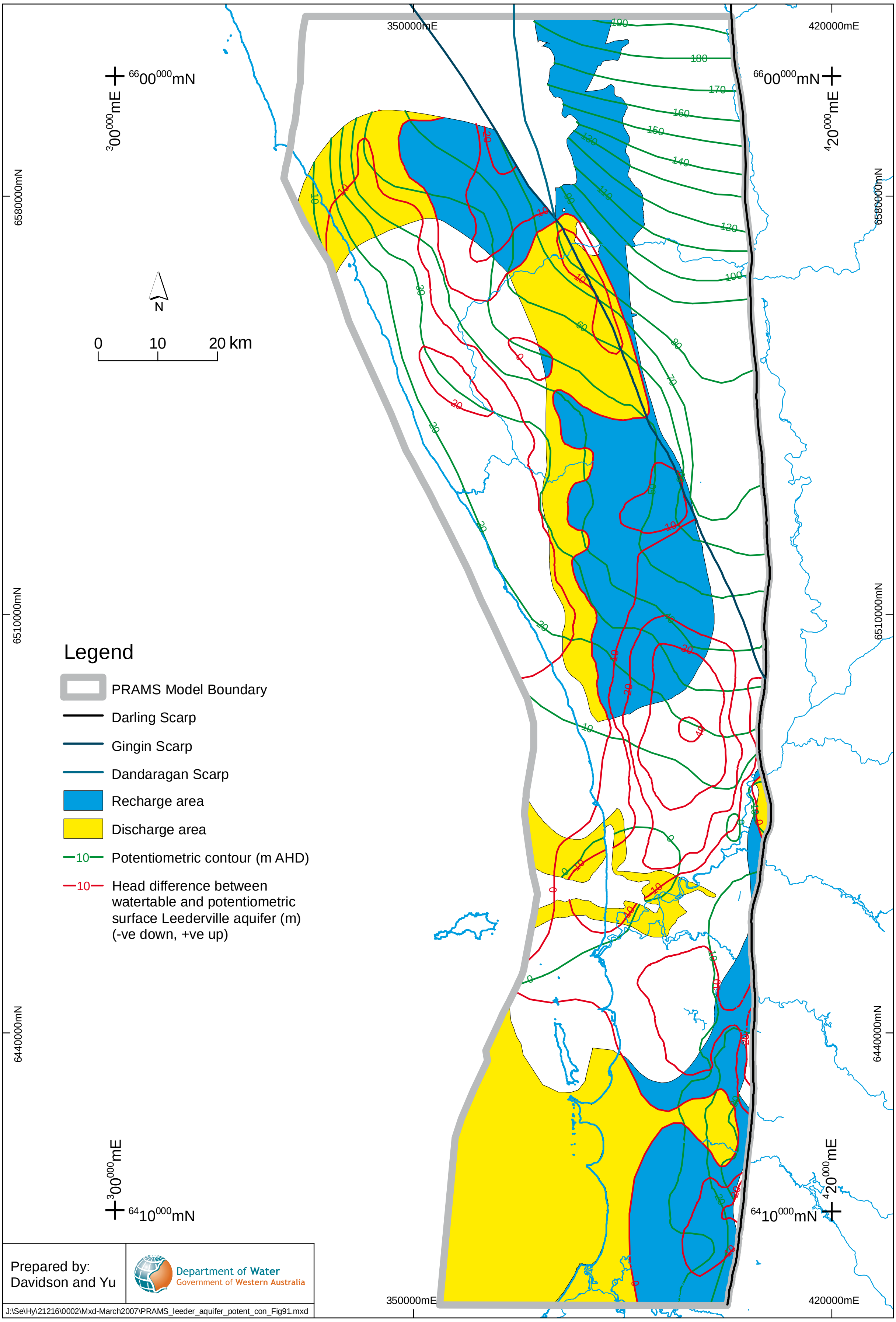


Figure 91 Leederville aquifer: potentiometric contours

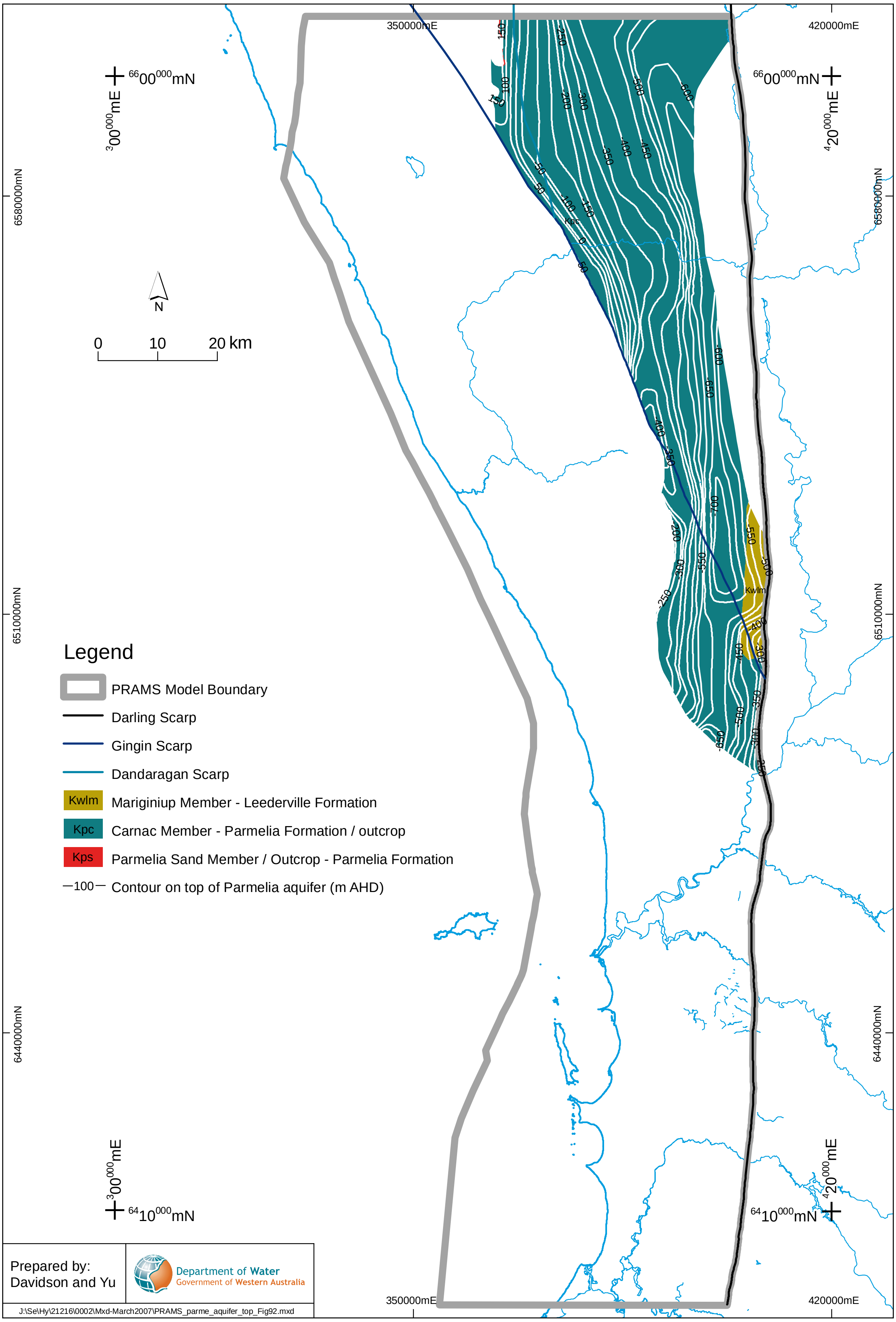


Figure 92 Parmelia Sand aquifer: contours on top of aquifer; with overlying strata

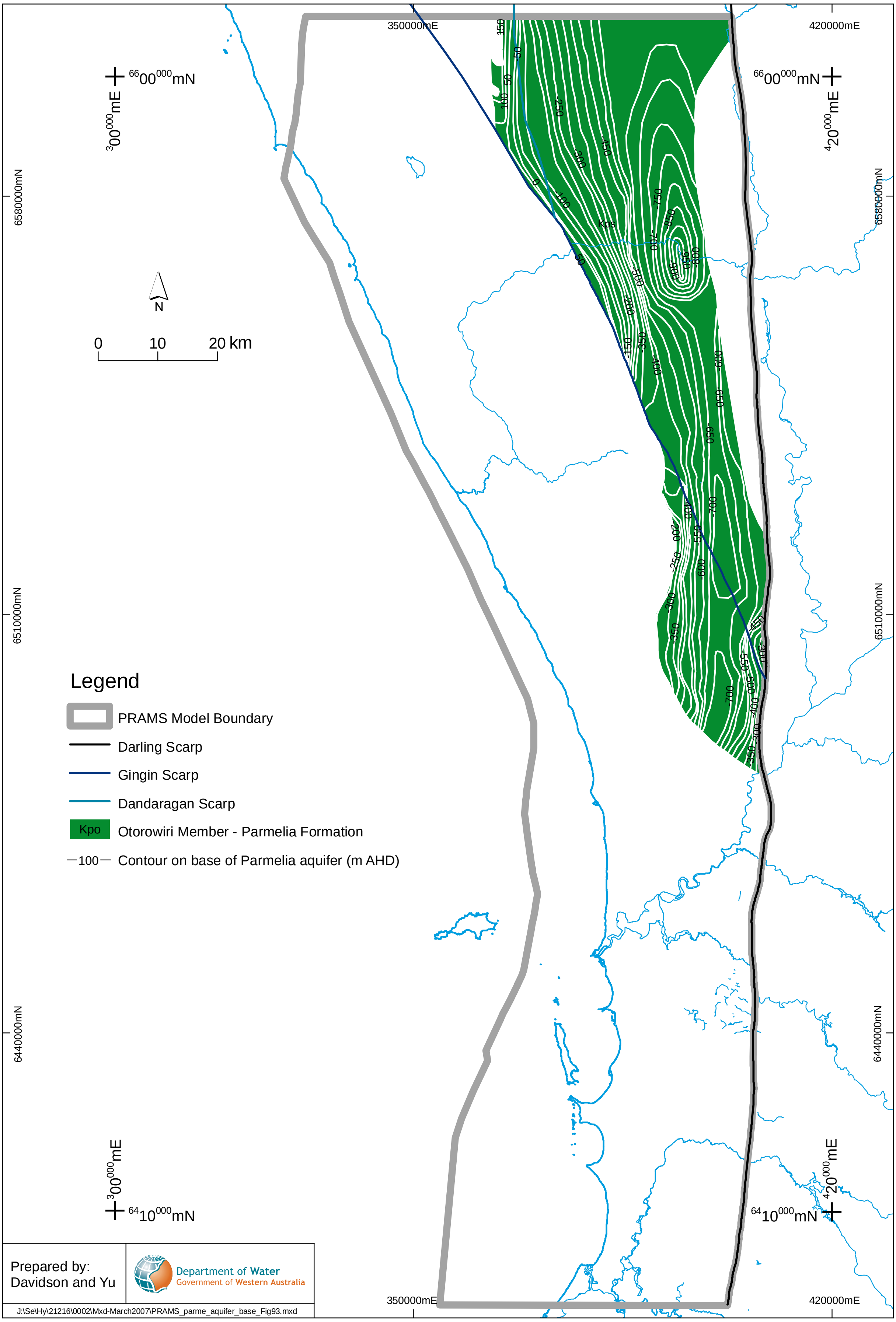


Figure 93 Parmelia Sand aquifer: contours on base of aquifer; with strata subcrop

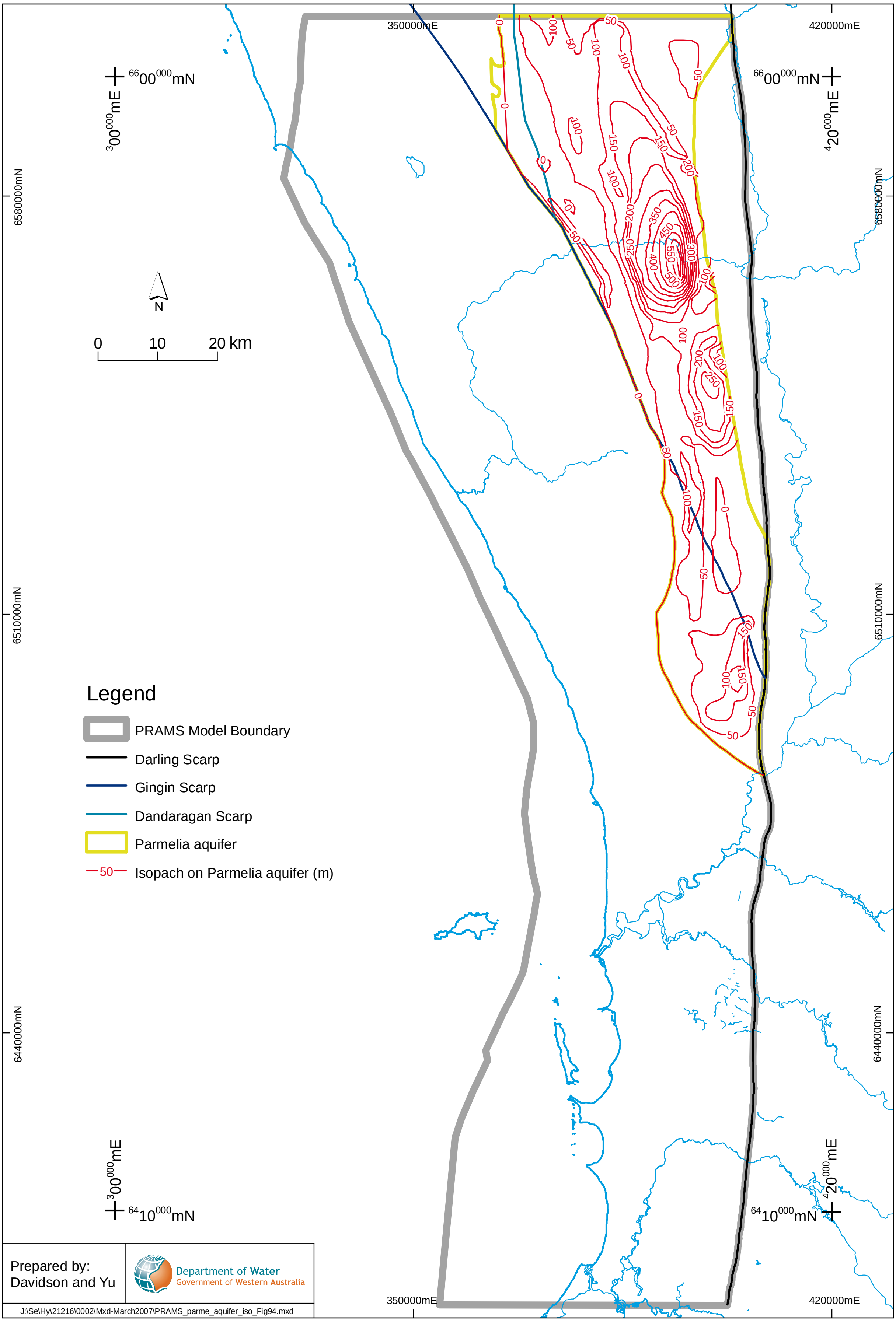


Figure 94 Parmelia Sand aquifer: isopachs

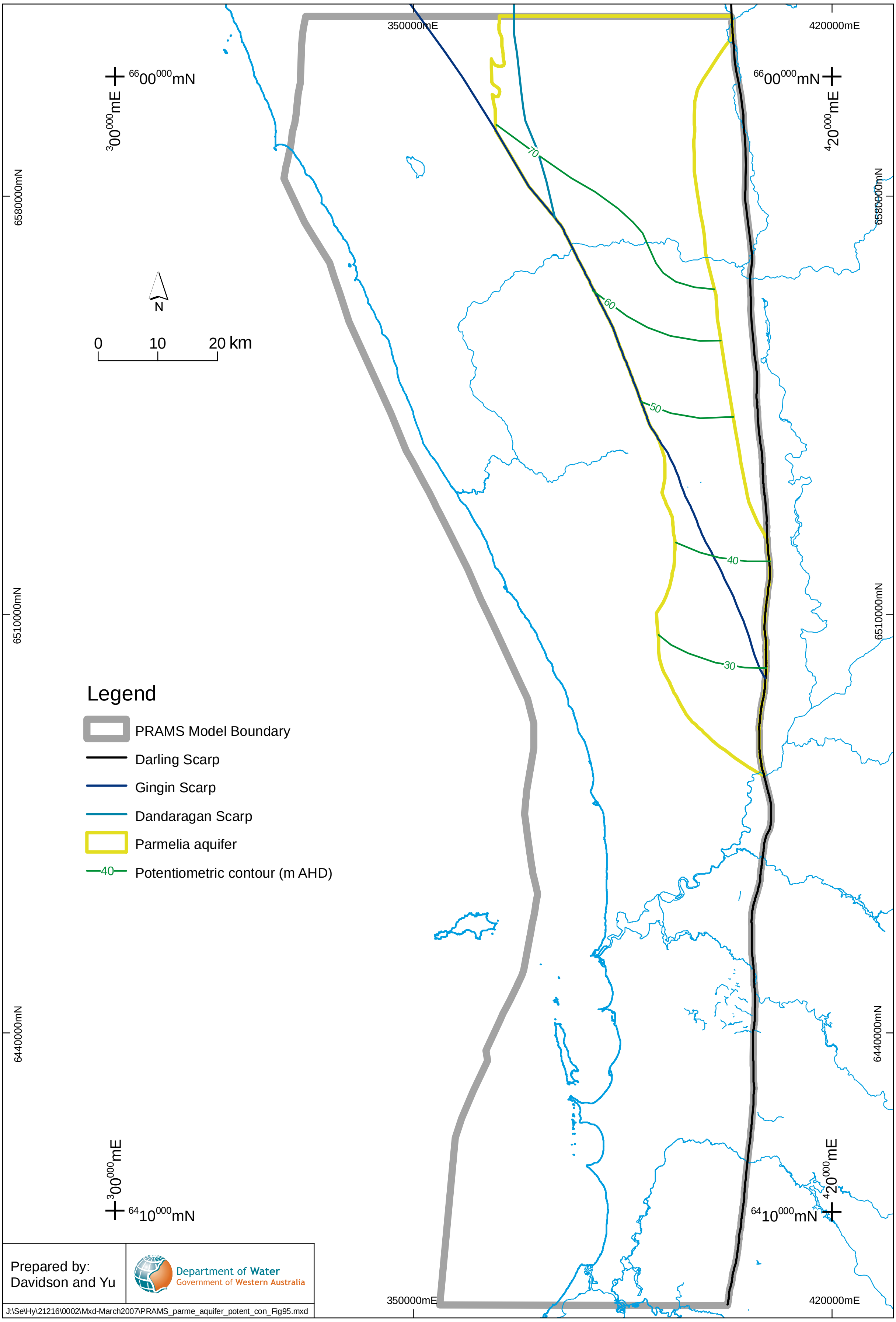


Figure 95 Parmelia Sand aquifer: potentiometric contours November 1997

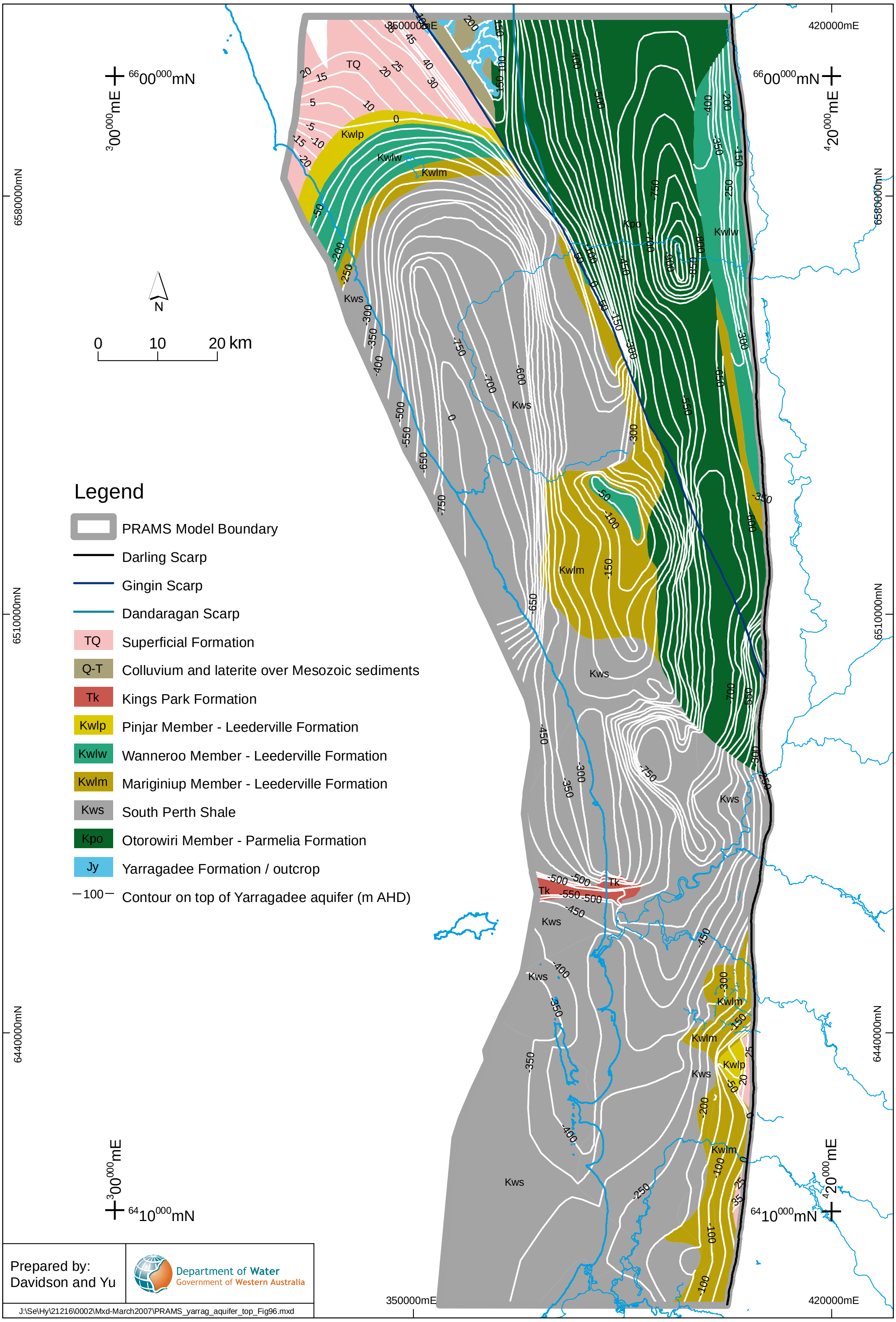


Figure 96 Yarragadee aquifer: contours on top of aquifer; with overlying strata

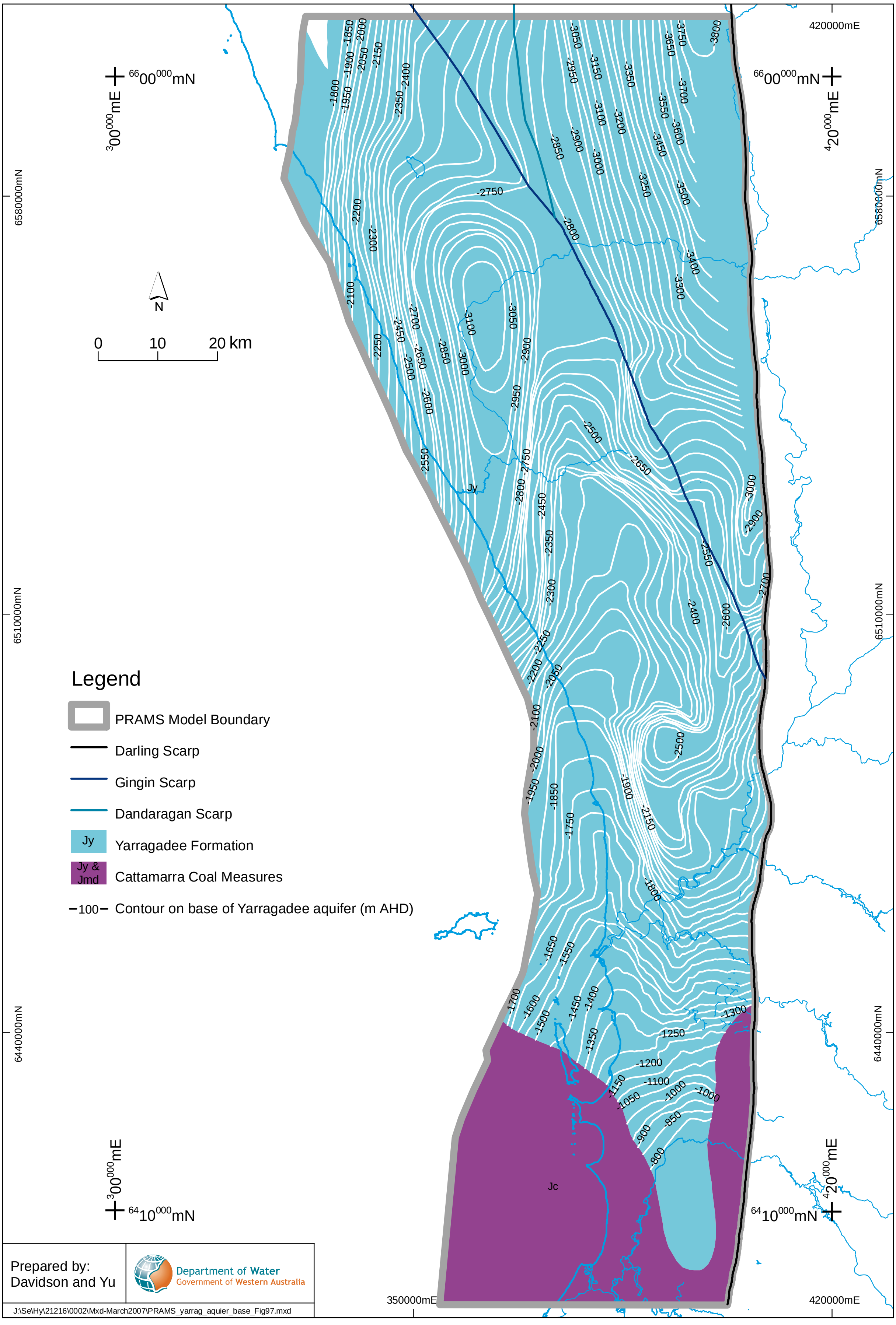


Figure 97 Yarragadee aquifer: contours on base of aquifer; with strata subcrop

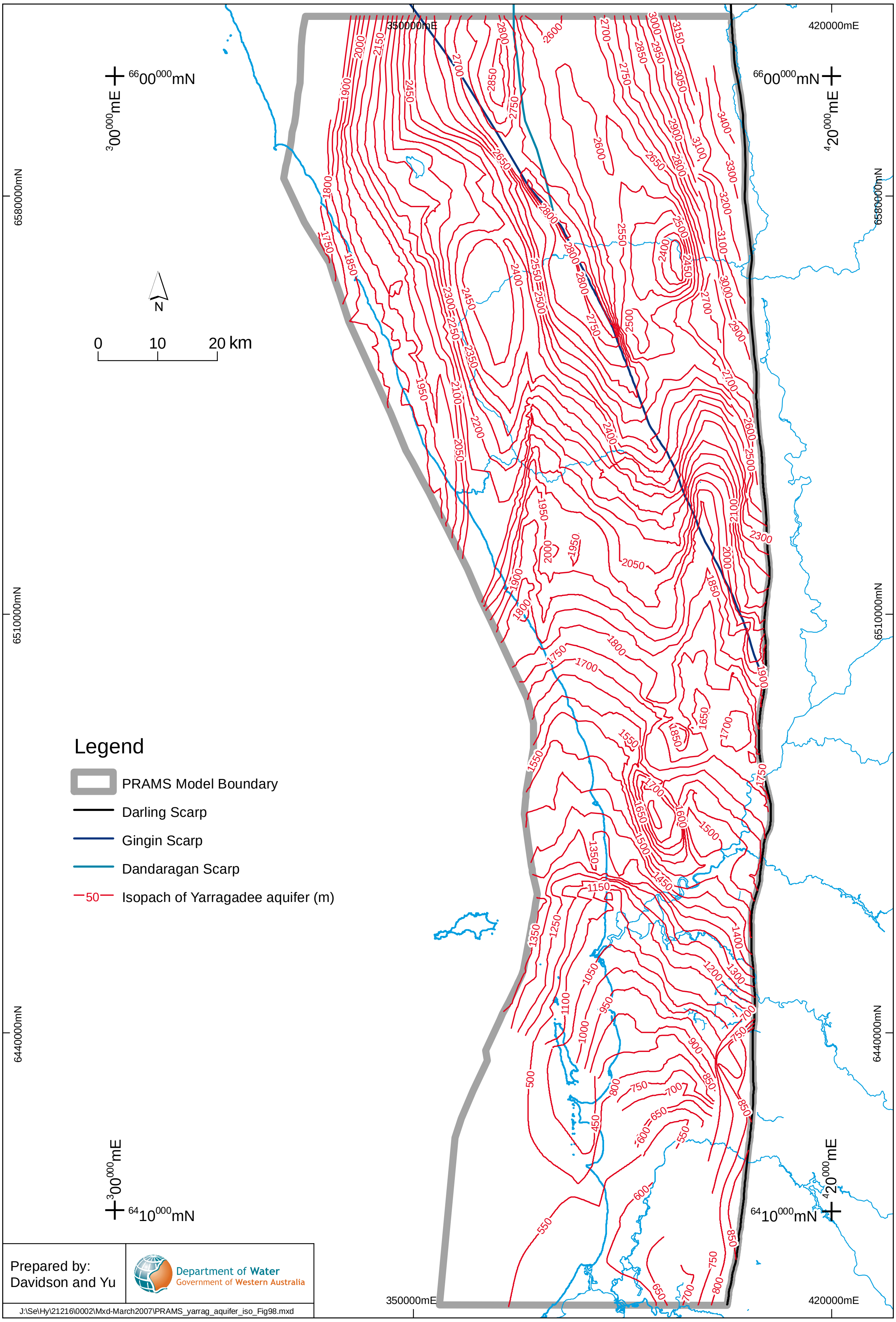


Figure 98 Yarragadee aquifer: isopachs

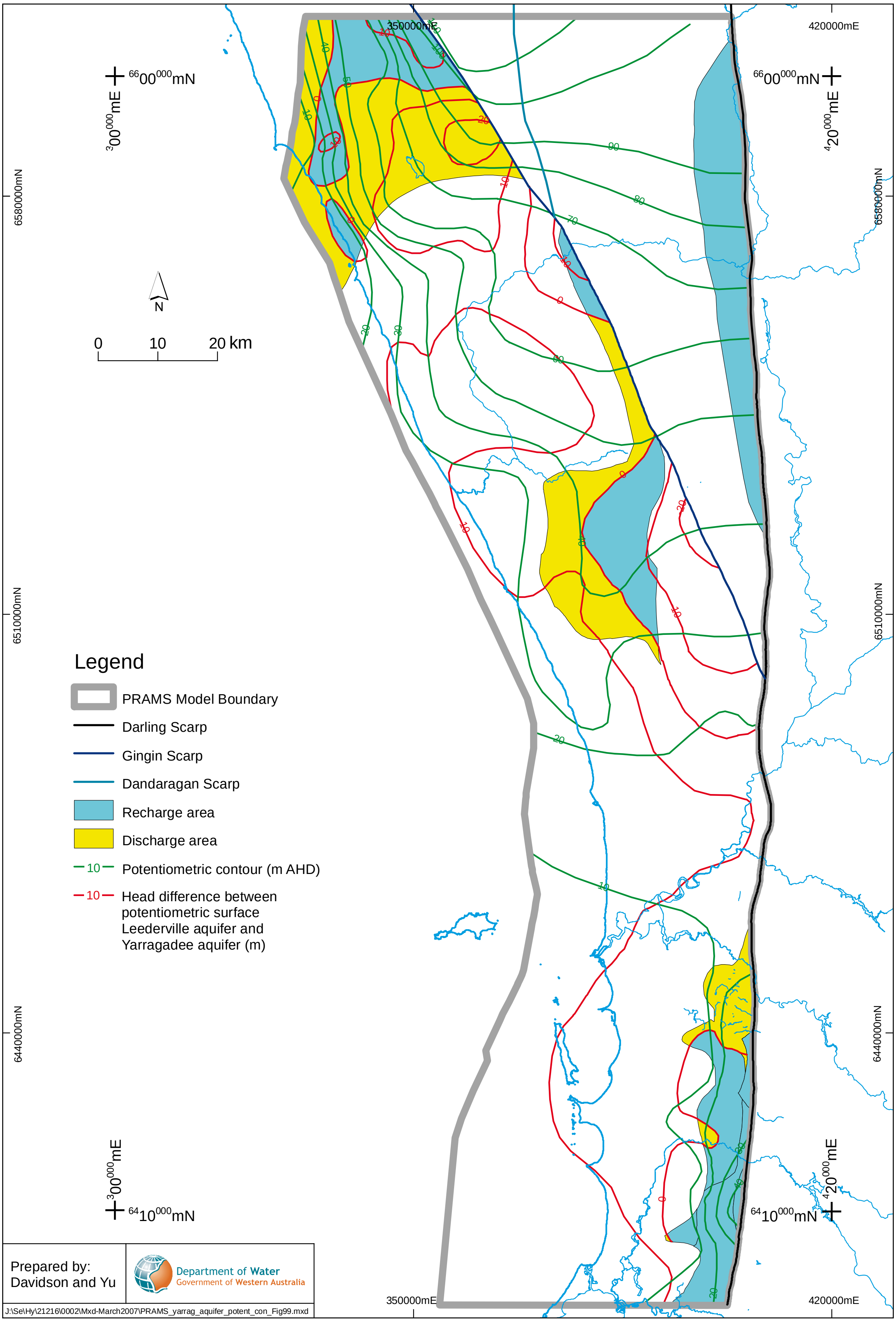


Figure 99 Yarragadee aquifer: potentiometric contours November 1997

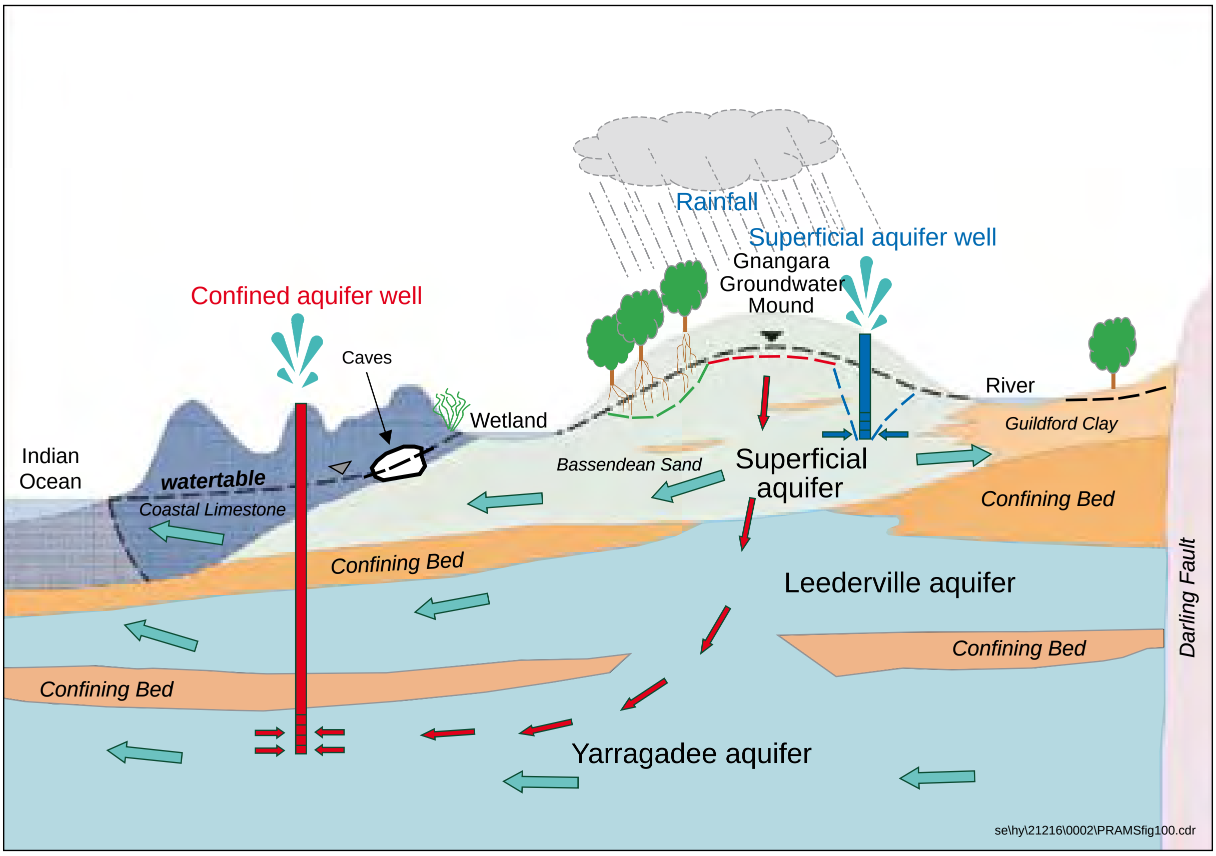


Figure 100 Diagrammatic representation of aquifer relationships

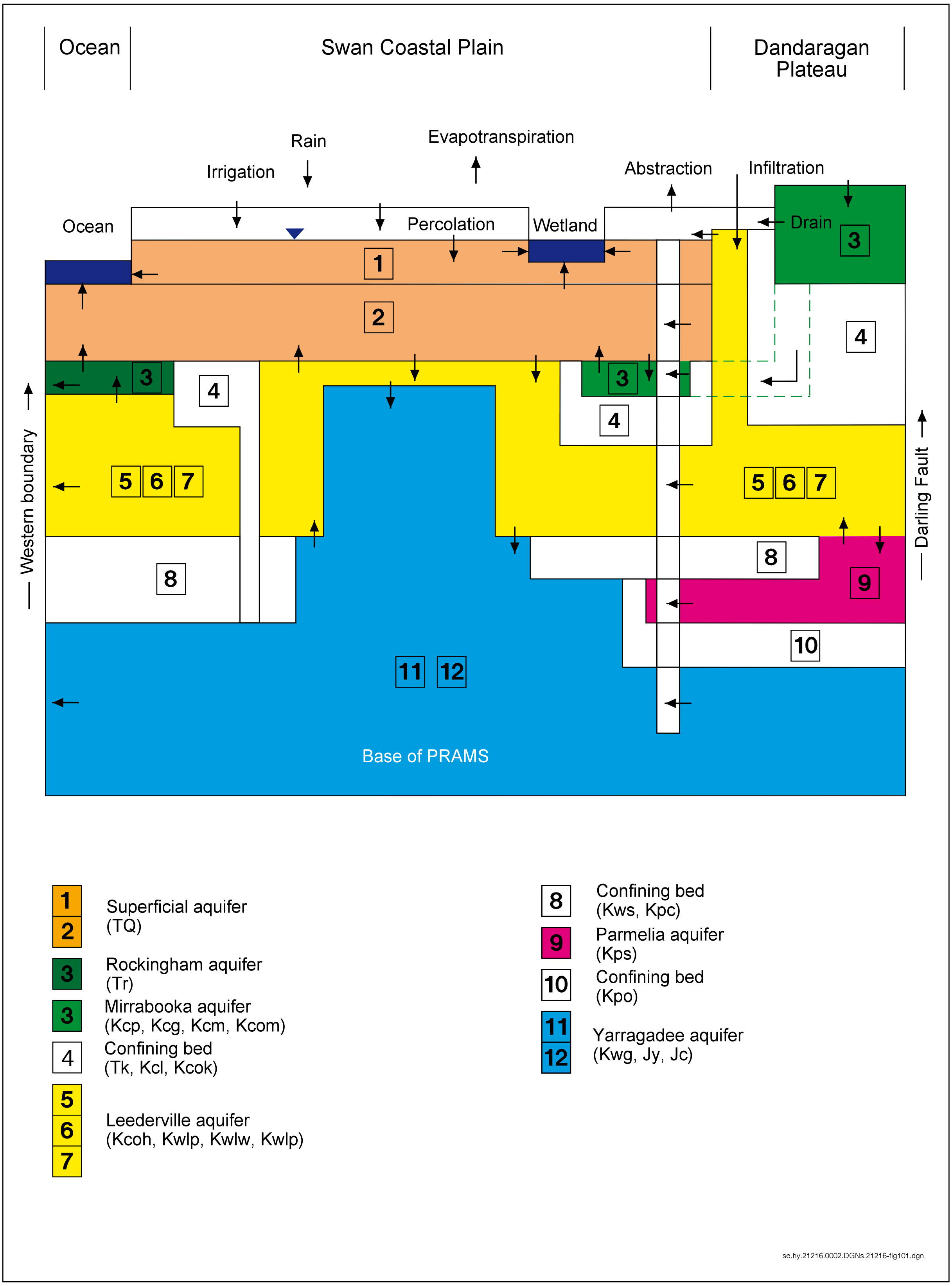


Figure 101 PRAMS conceptual model and design showing hydrological processes in the aquifer system

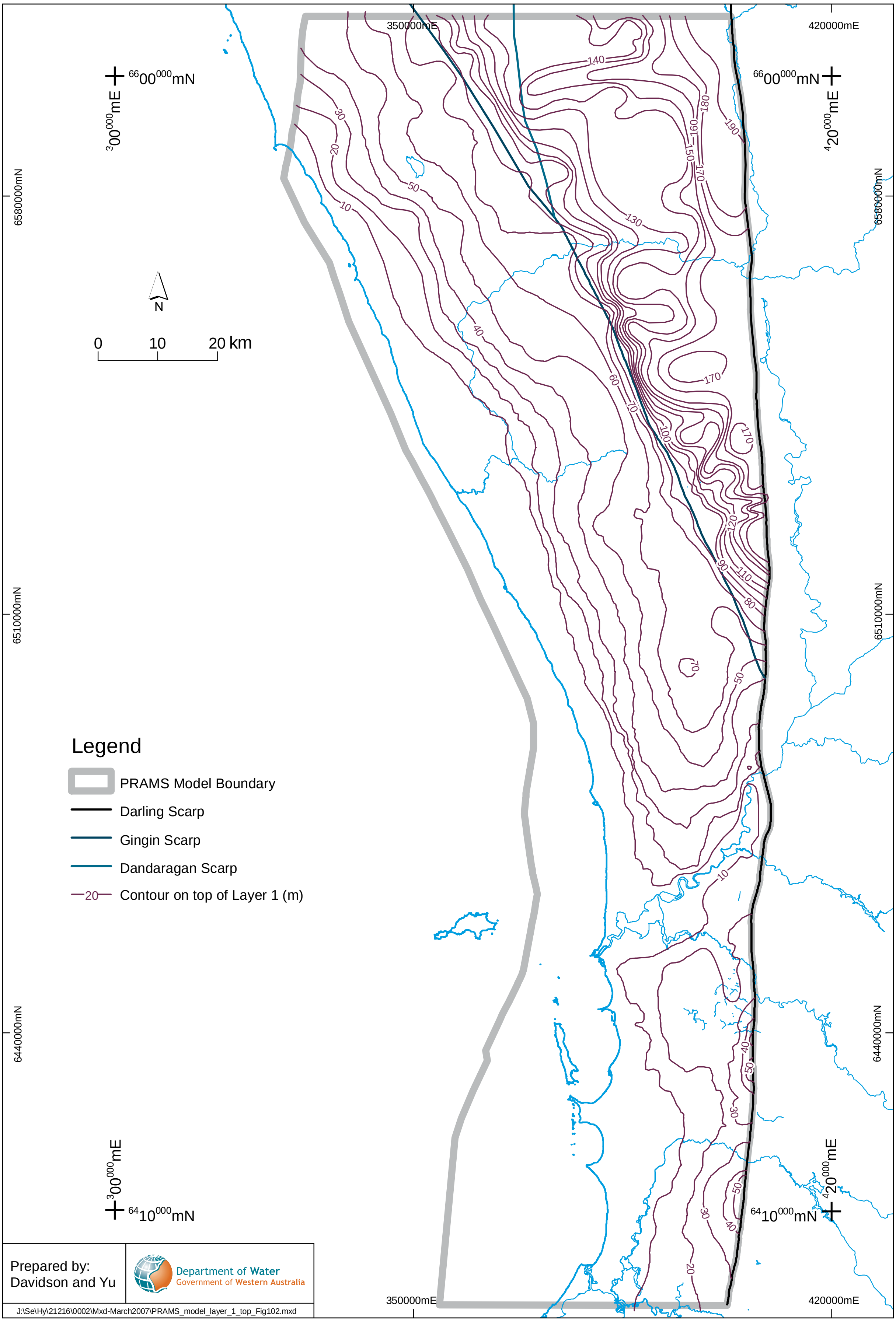


Figure 102 PRAMS model Layer 1 – Superficial aquifer: contours on top of Layer 1

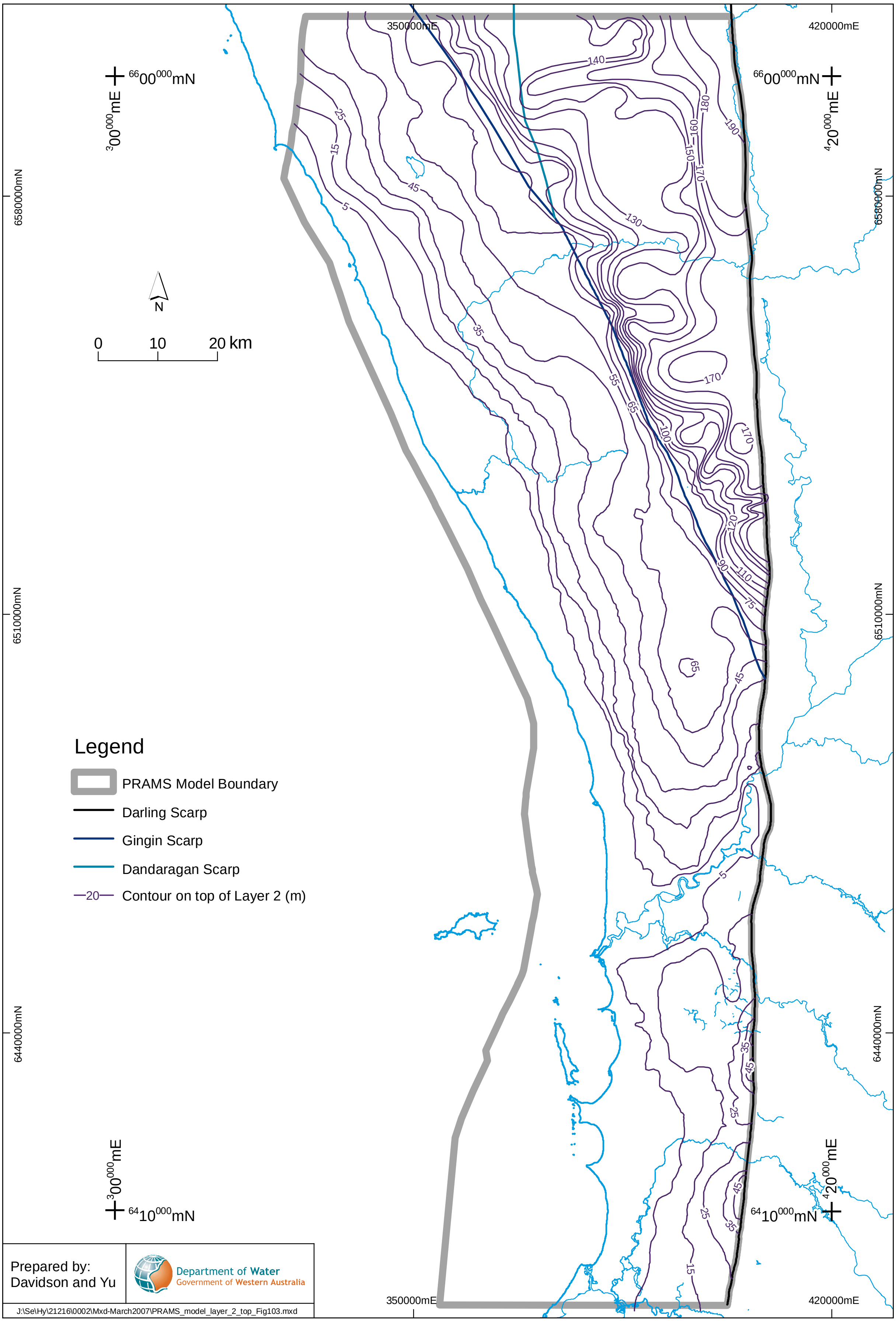


Figure 103 PRAMS model Layer 2 – Superficial aquifer: contours on top of Layer 2

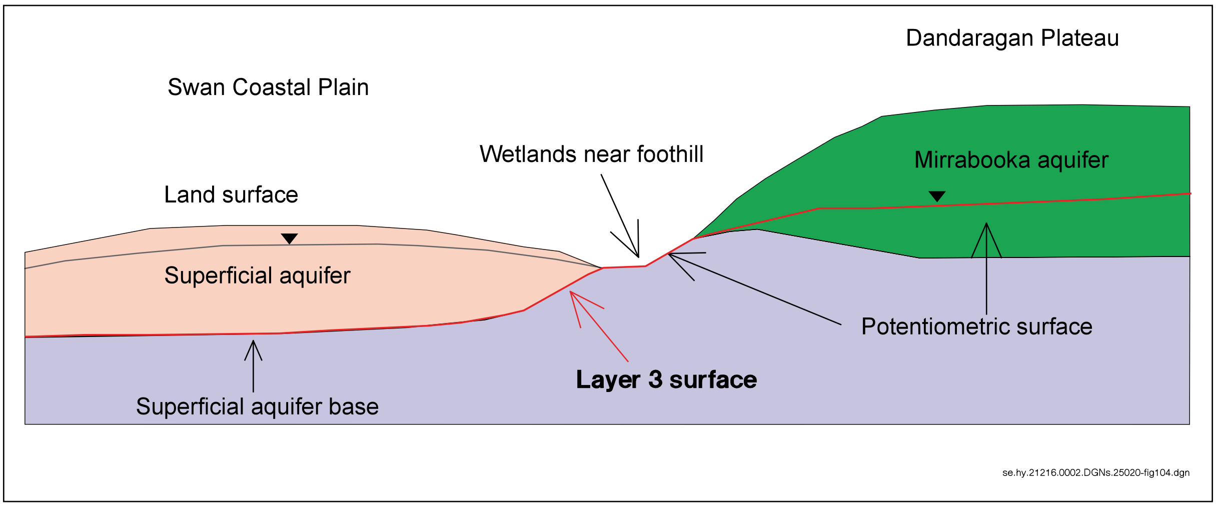


Figure 104 Mirrabooka aquifer: schematic section of Layer 3 near the Gingin Scarp

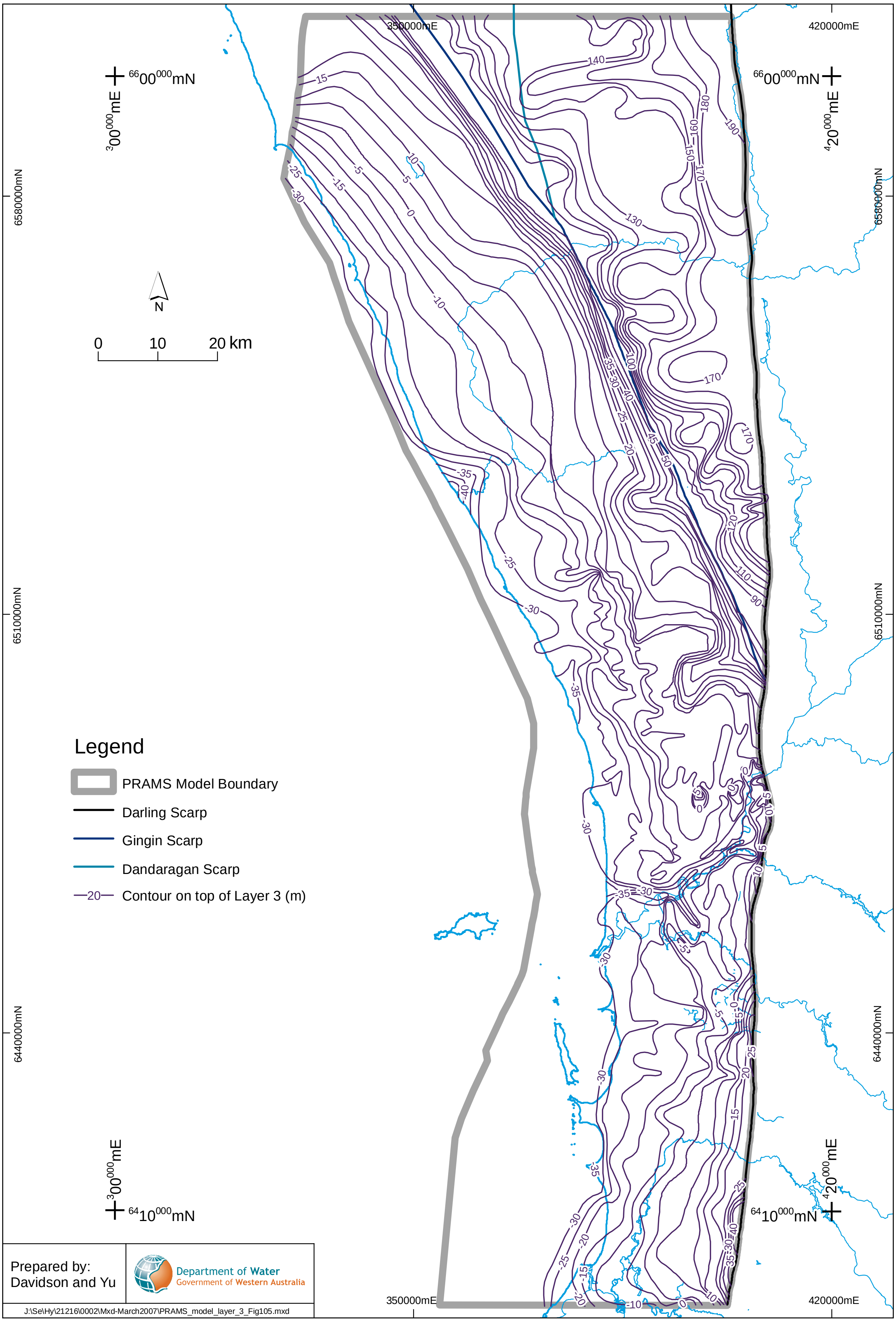


Figure 105 PRAMS model Layer 3 – Rockingham/Mirrabooka aquifer: contours on top of Layer 3

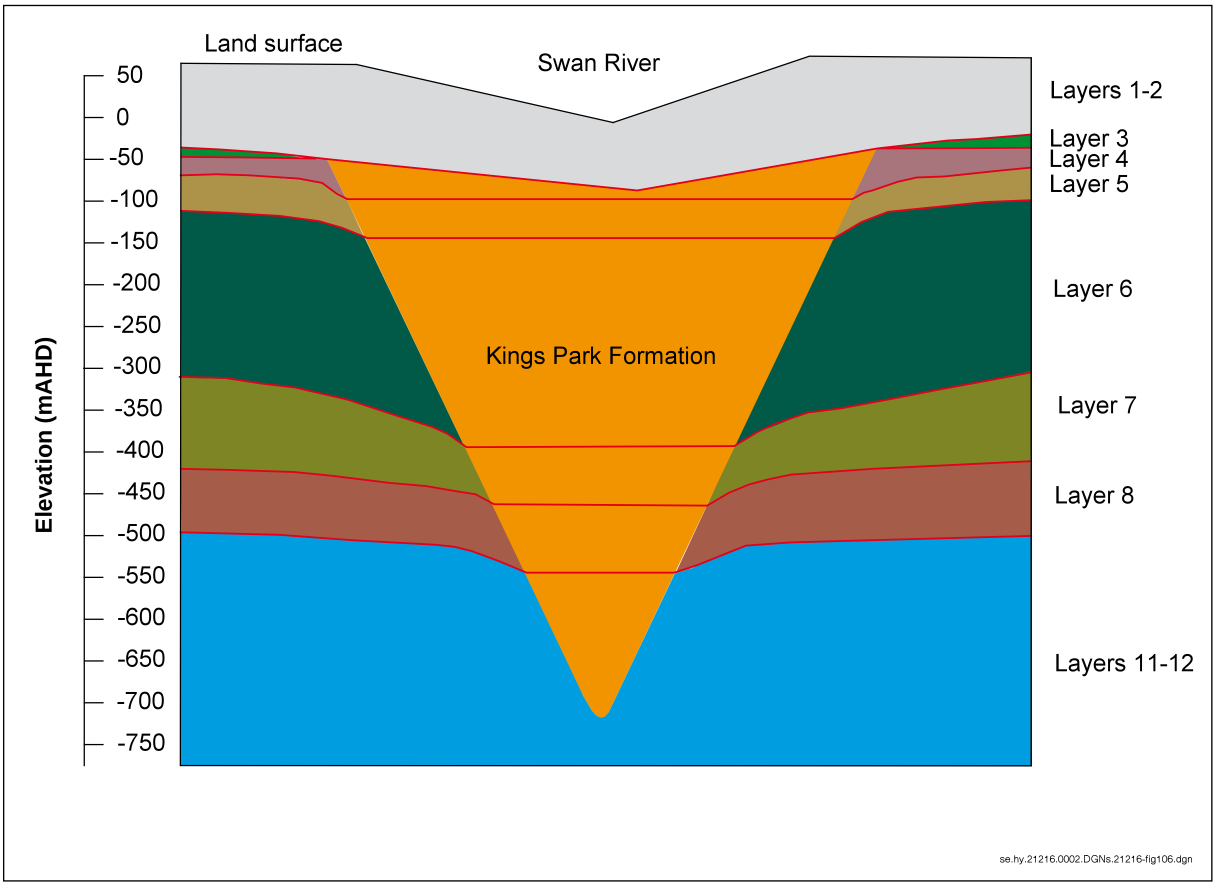


Figure 106 Kings Park Formation: schematic section of model layers surrounding the Kings Park Formation

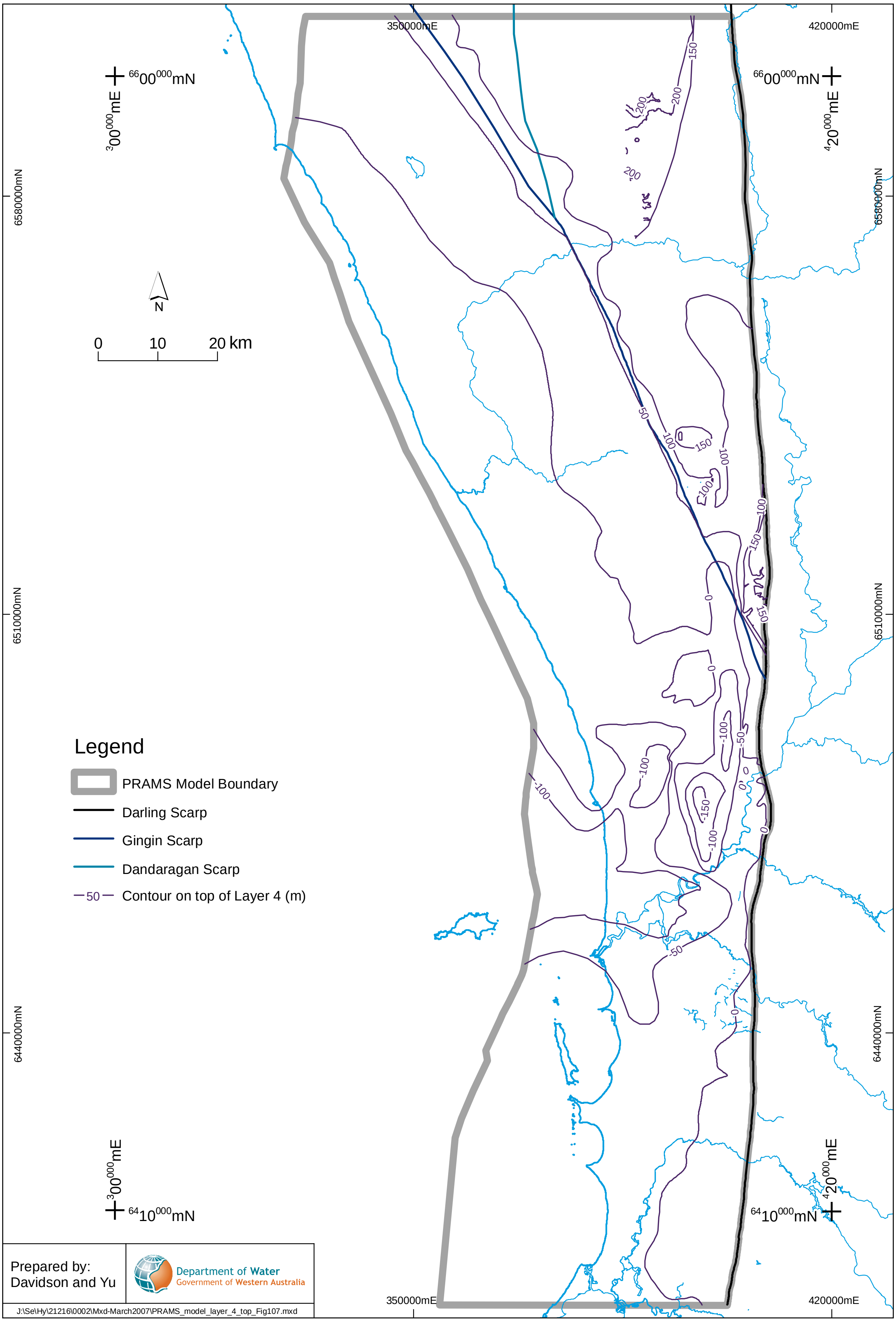


Figure 107 PRAMS model Layer 4 – Confining bed consisting of either the Kings Park Formation, Lancelin Formation, or Kardinya Shale: contours on top of Layer 4

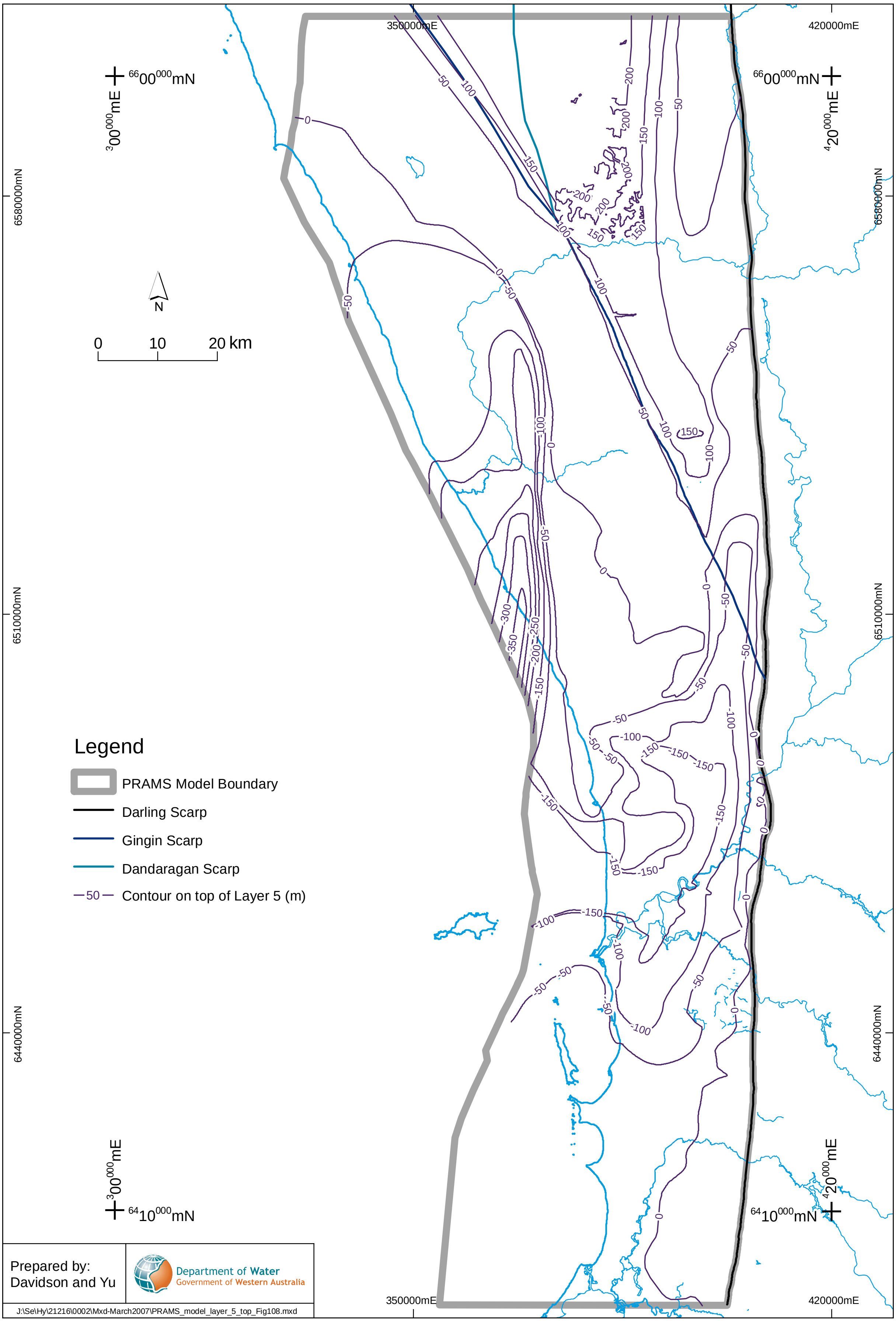


Figure 108 PRAMS model Layer 5 – Henley Sandstone/Pinjar Member of the Leederville aquifer: contours on top of Layer 5

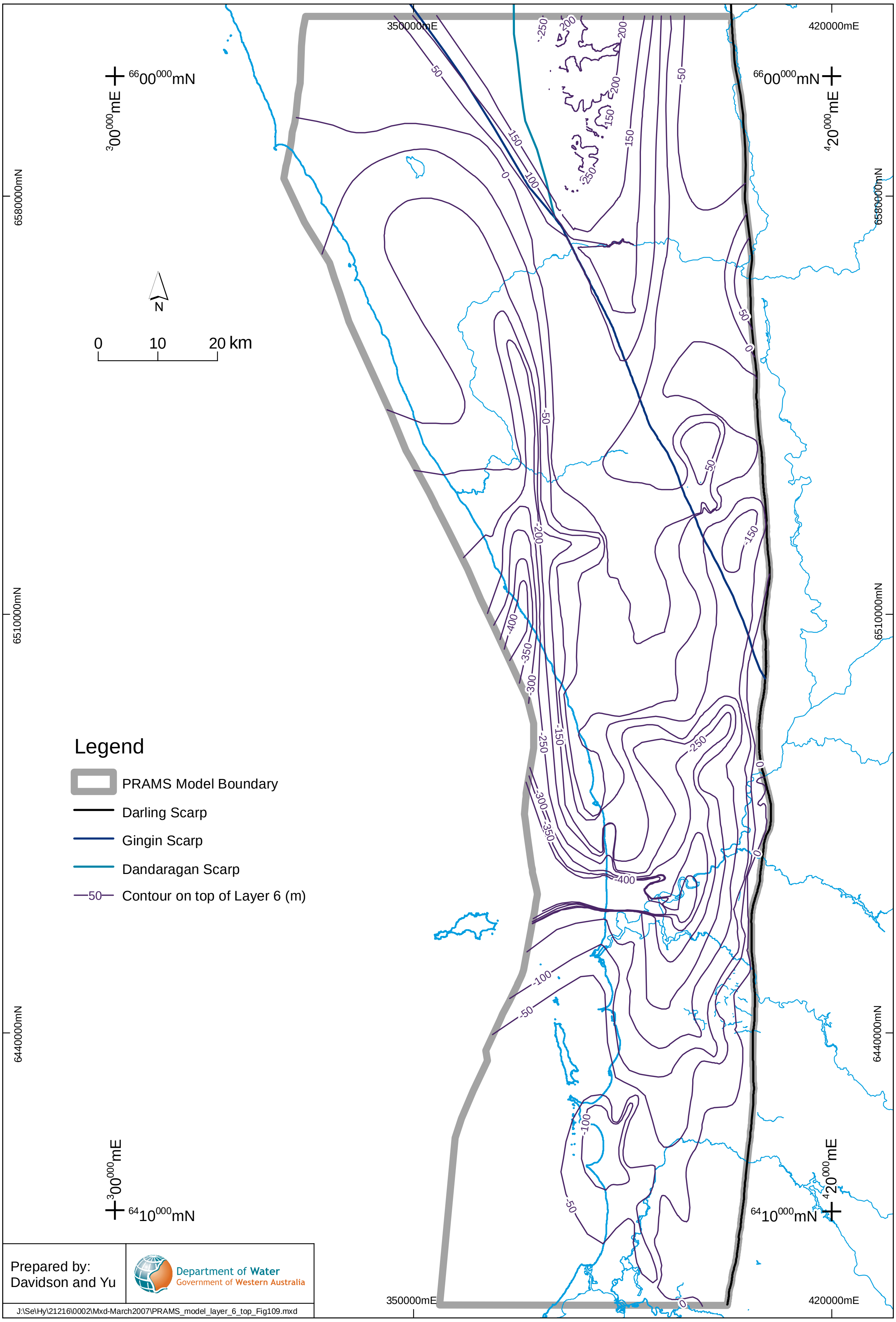


Figure 109 PRAMS model Layer 6 – Wanneroo Member of the Leederville aquifer: contours on top of Layer 6

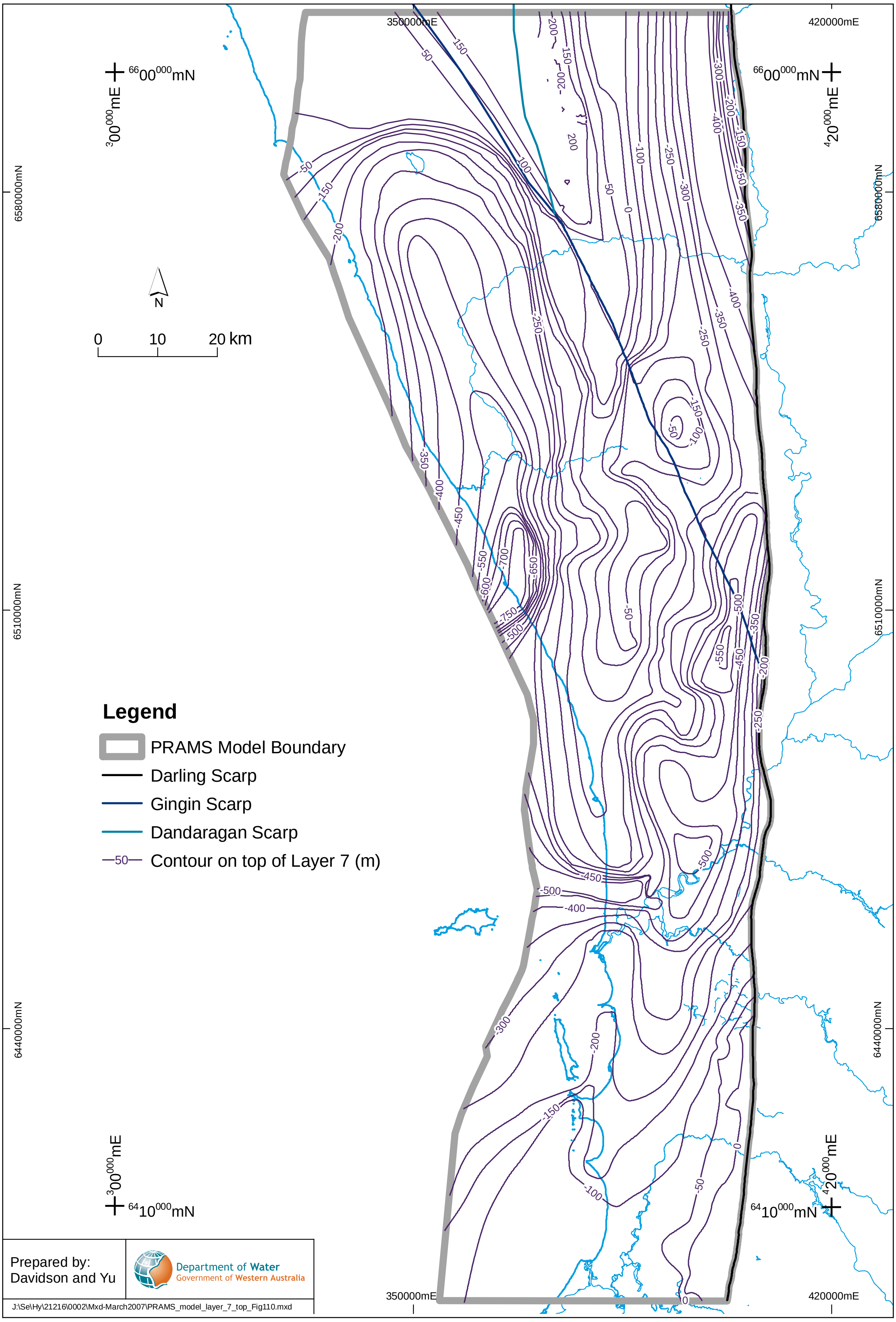


Figure 110 PRAMS model Layer 7 – Mariginiup Member of the Leederville aquifer: contours on top of Layer 7

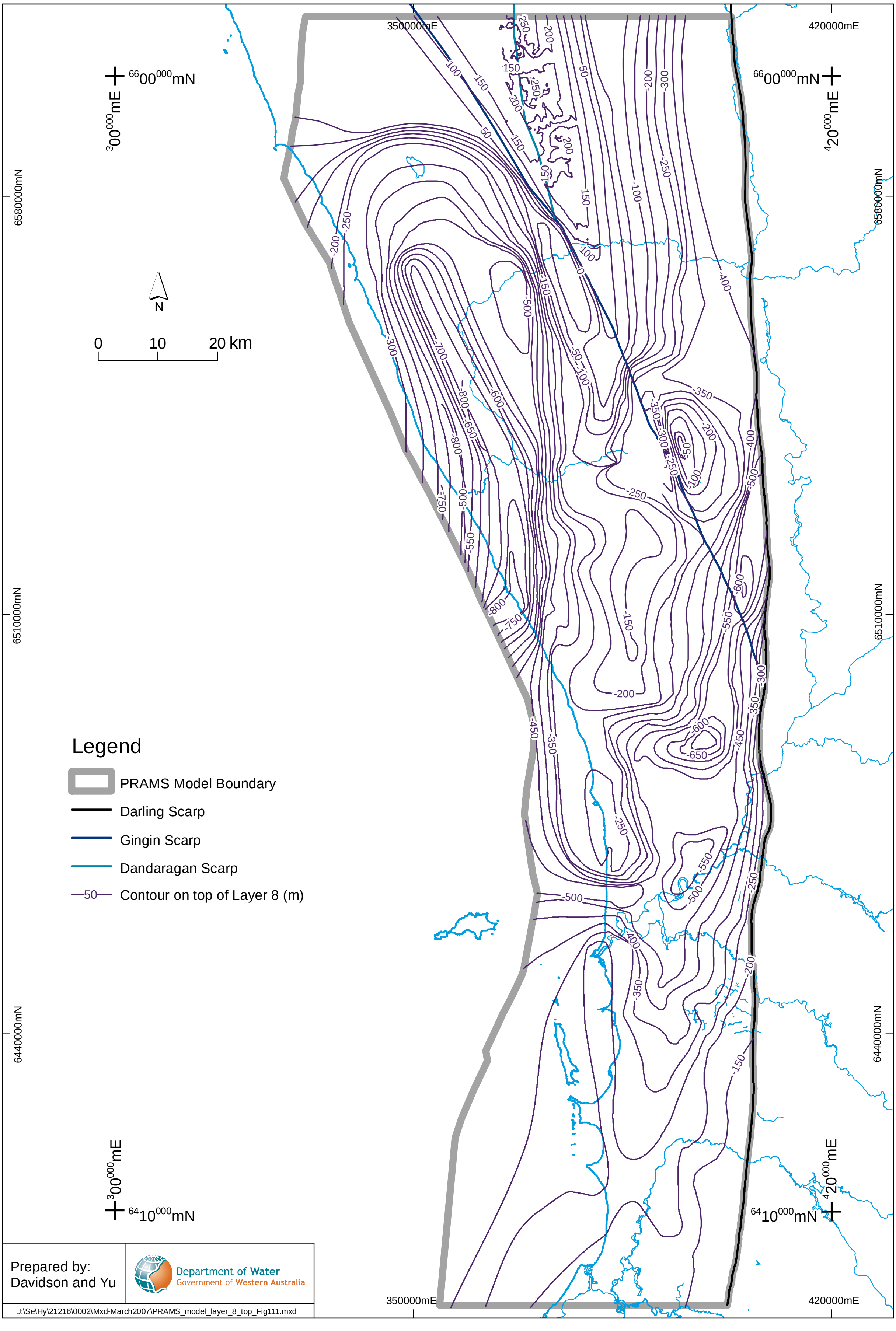


Figure 111 PRAMS model Layer 8 – Confining bed consisting of either the South Perth Shale or Carnac Member: contours on top of Layer 8

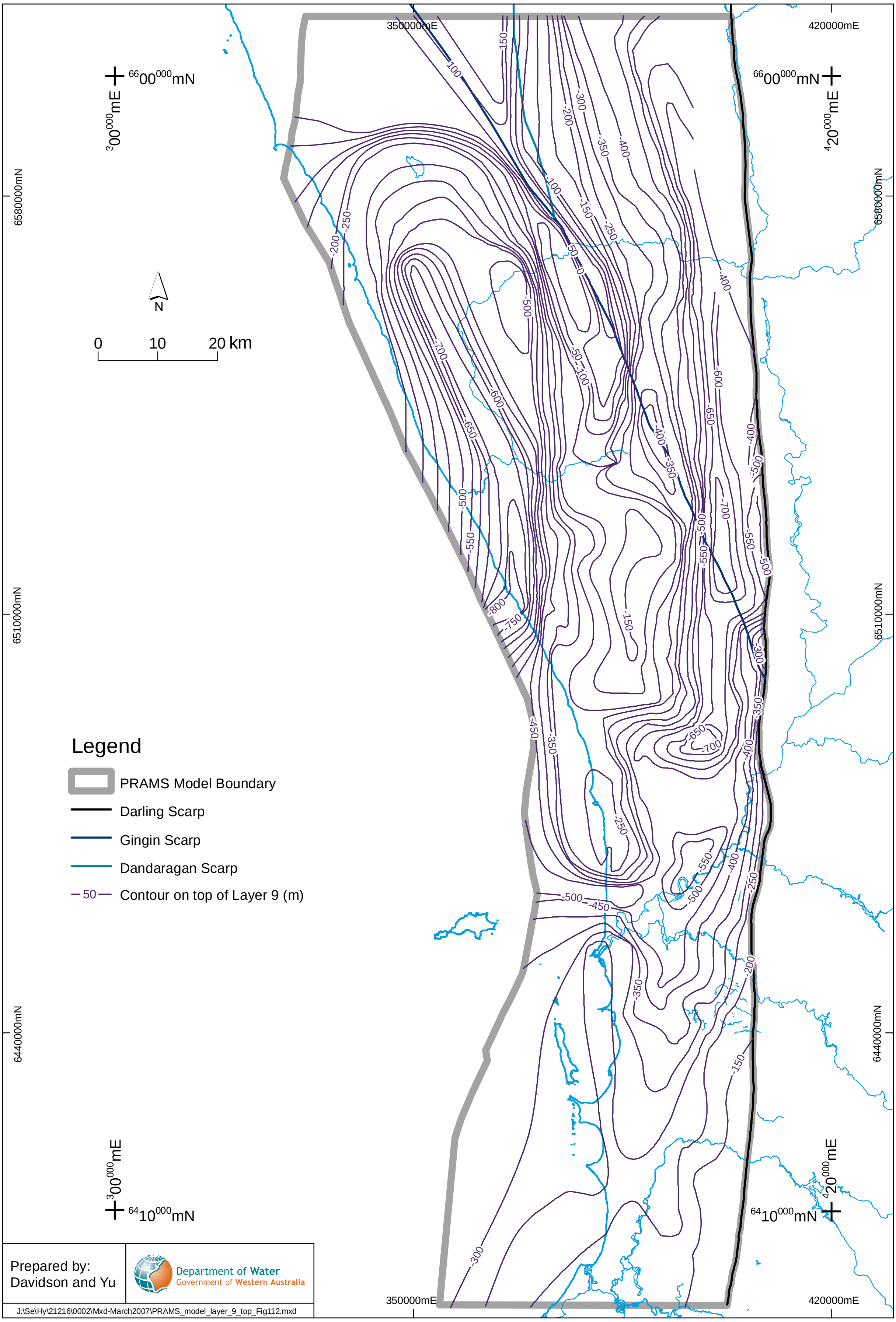


Figure 112 PRAMS model Layer 9 – Parmelia Sand aquifer: contours on top of Layer 9

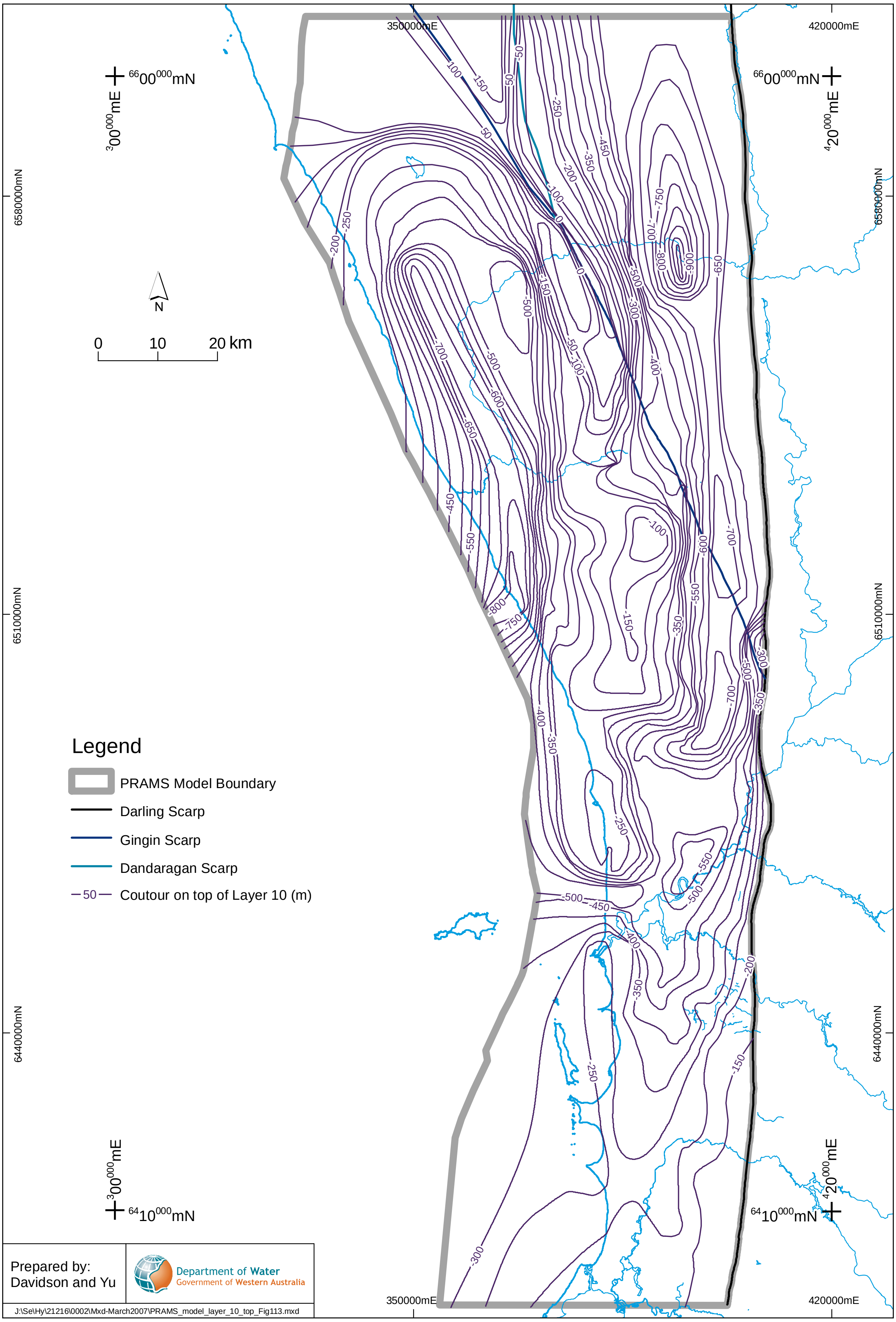


Figure 113 PRAMS model Layer 10 – Confining bed consisting of Otorowiri Member: contours on top of Layer 10

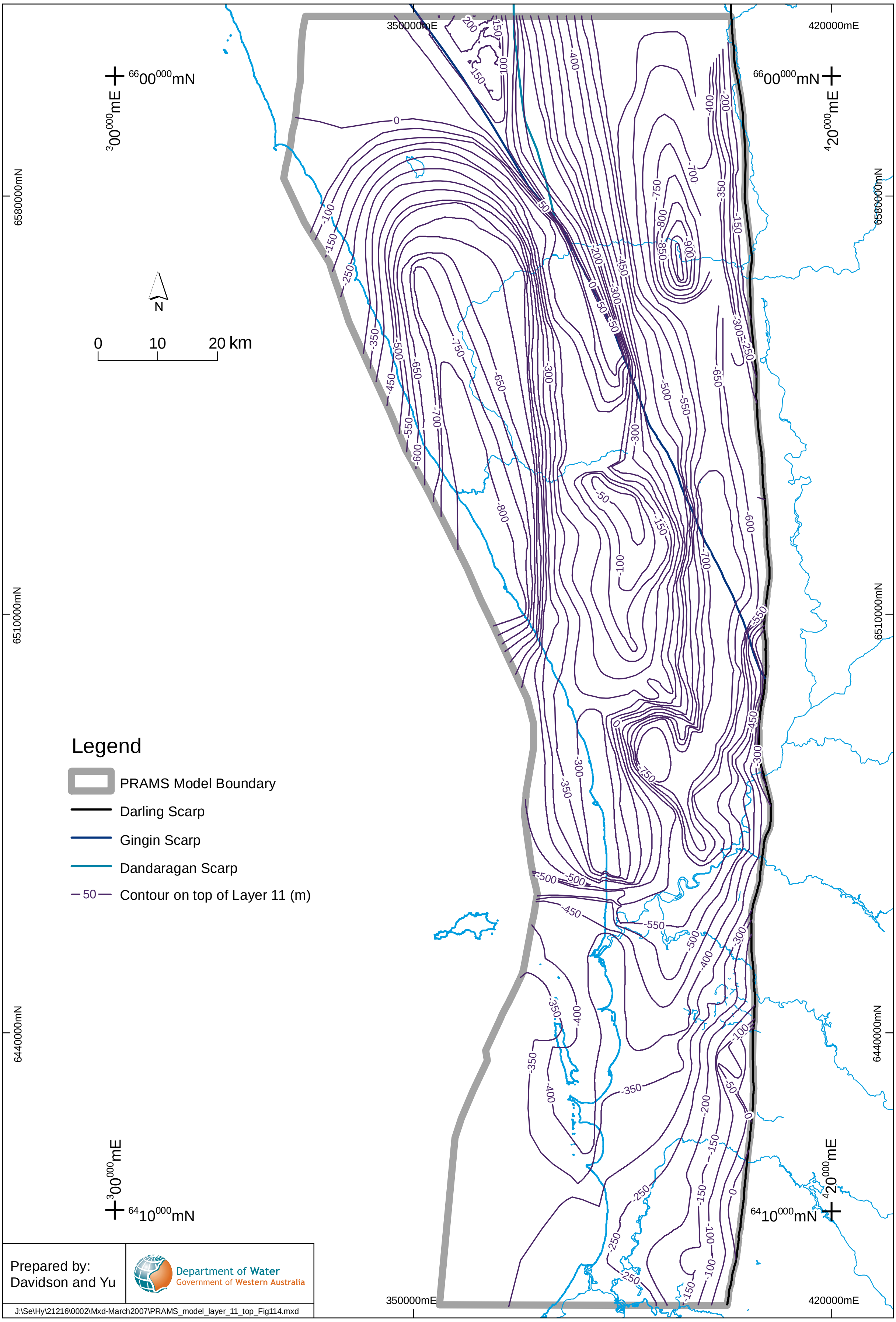


Figure 114 PRAMS model Layer 11 – Yarragadee aquifer: contours on top of Layer 11

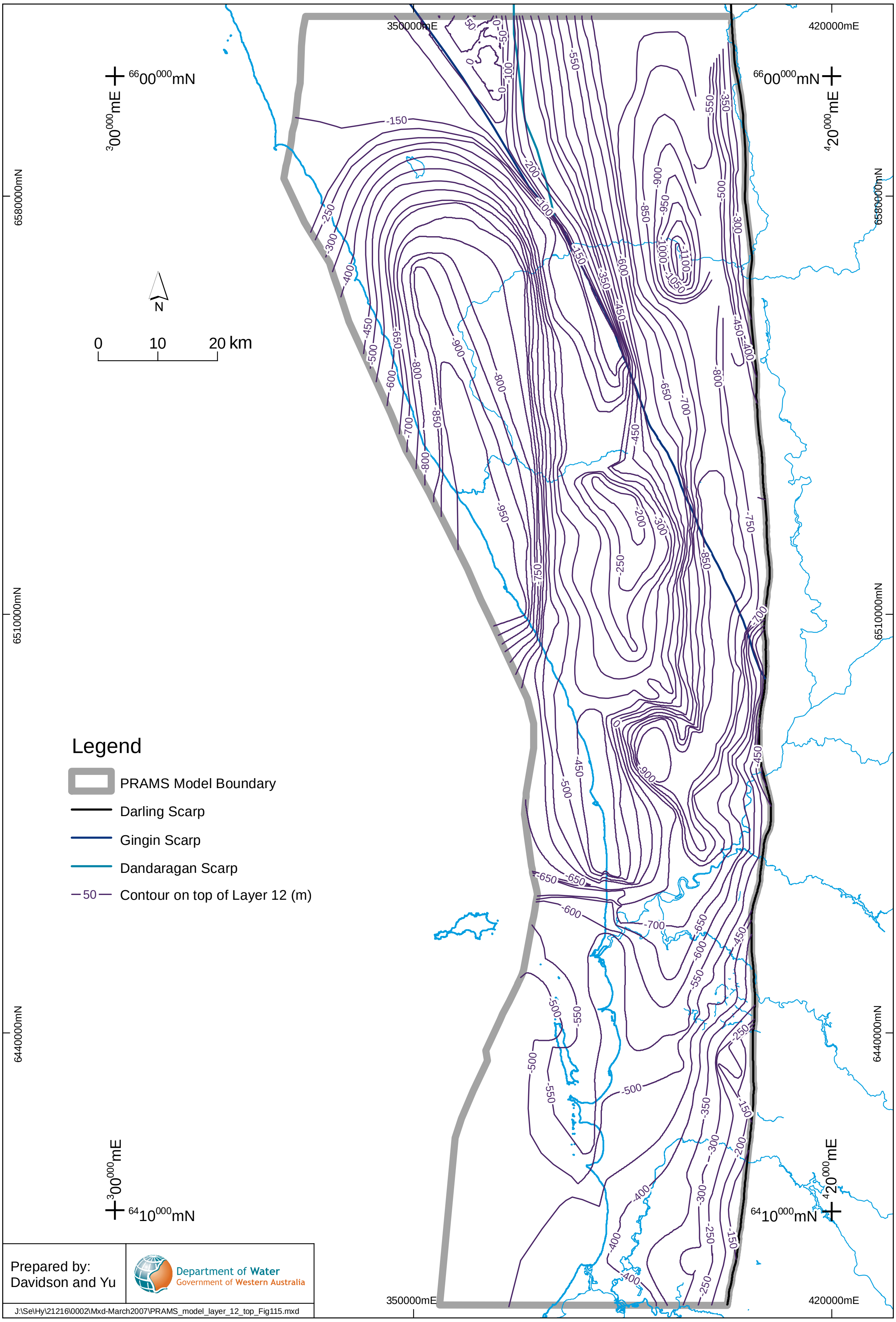


Figure 115 PRAMS model Layer 12 – Yarragadee aquifer: contours on top of Layer 12

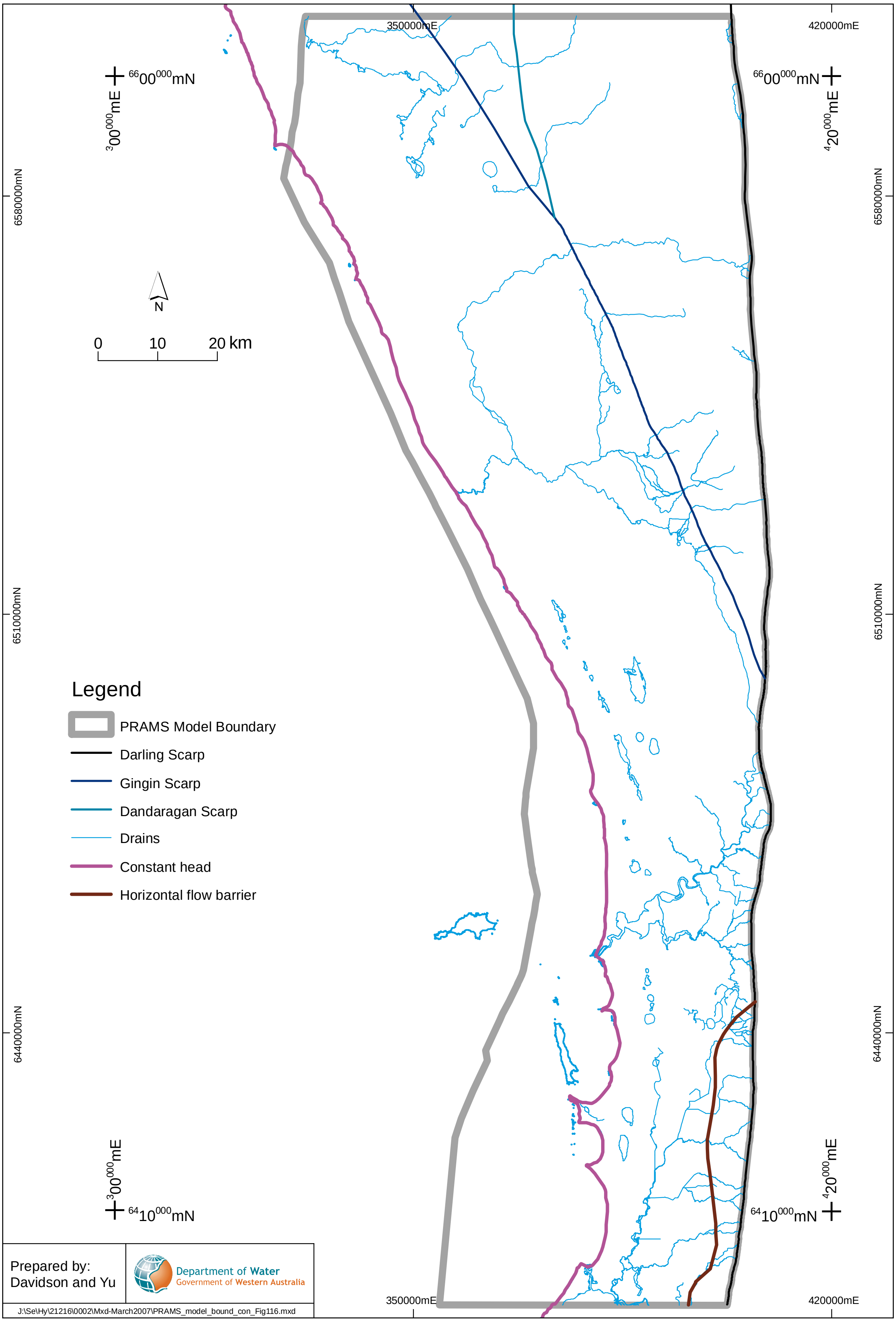


Figure 116 PRAMS model boundary conditions

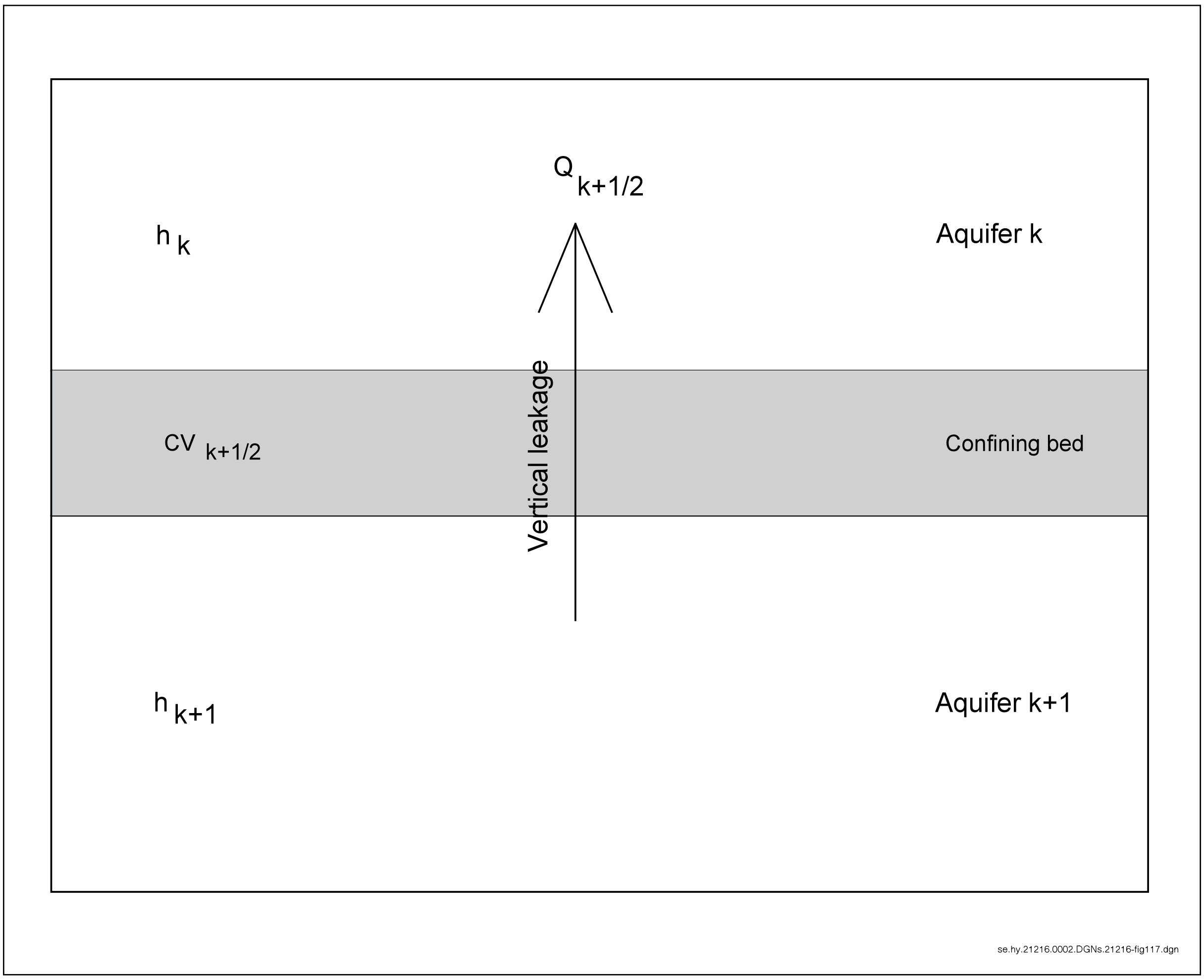
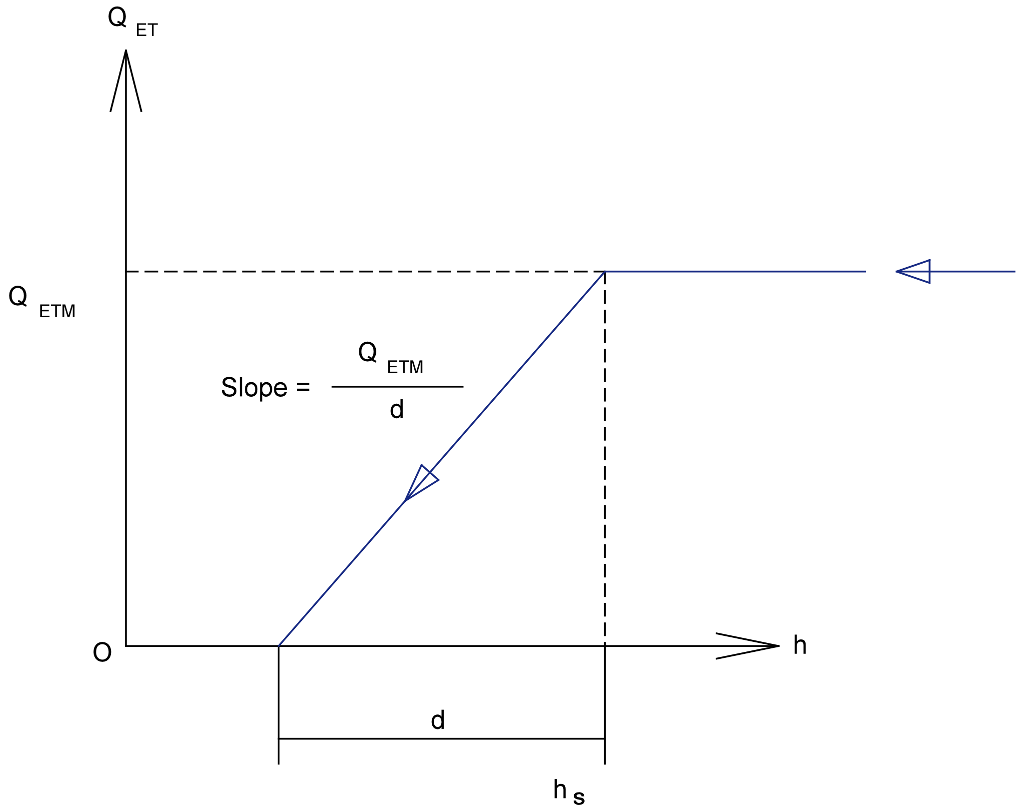


Figure 117 Vertical flux between confined aquifers: schematic section (after McDonald and Harbaugh, 1988)



Q_{ET} = volumetric evapotranspiration or a function of head h

Q_{ETM} = maximum evapotranspiration

d = the cutoff extinction depth beyound which ET will be neglected

h_s= the ET surface elevation

Figure 118 Evapotranspiration model in Modflow (after McDonald and Harbaugh, 1988)

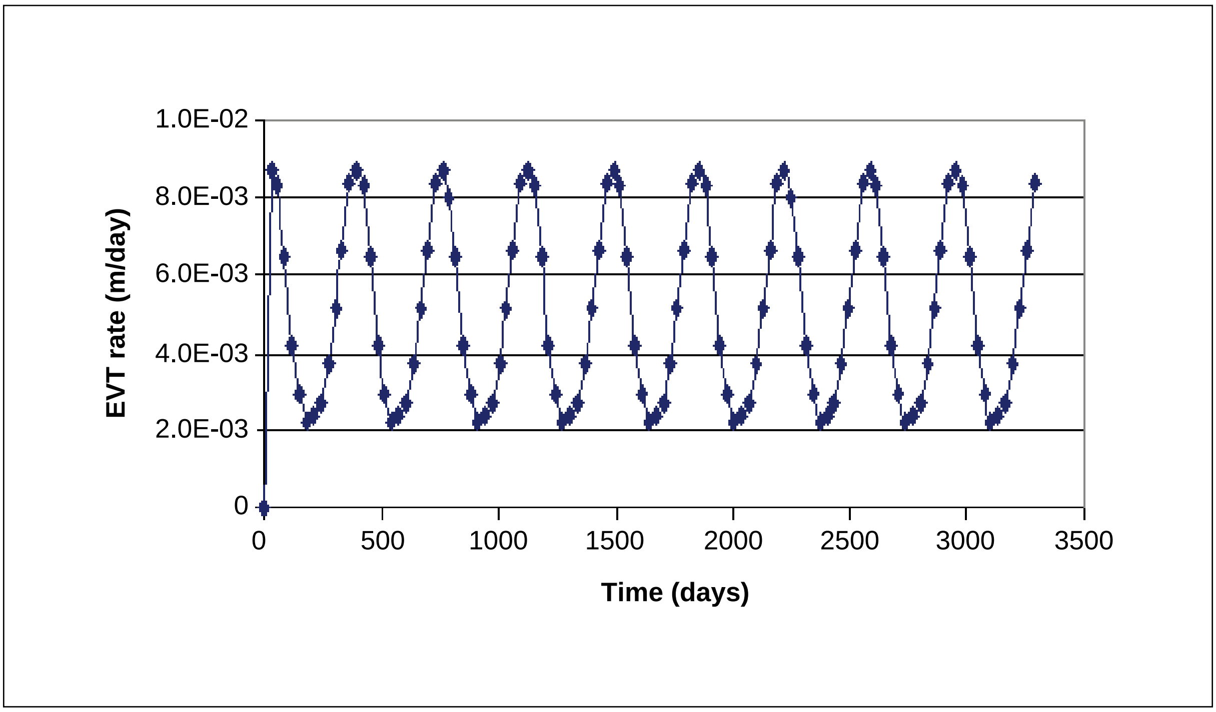


Figure 119 Calculated evapotranspiration rate as a function of time

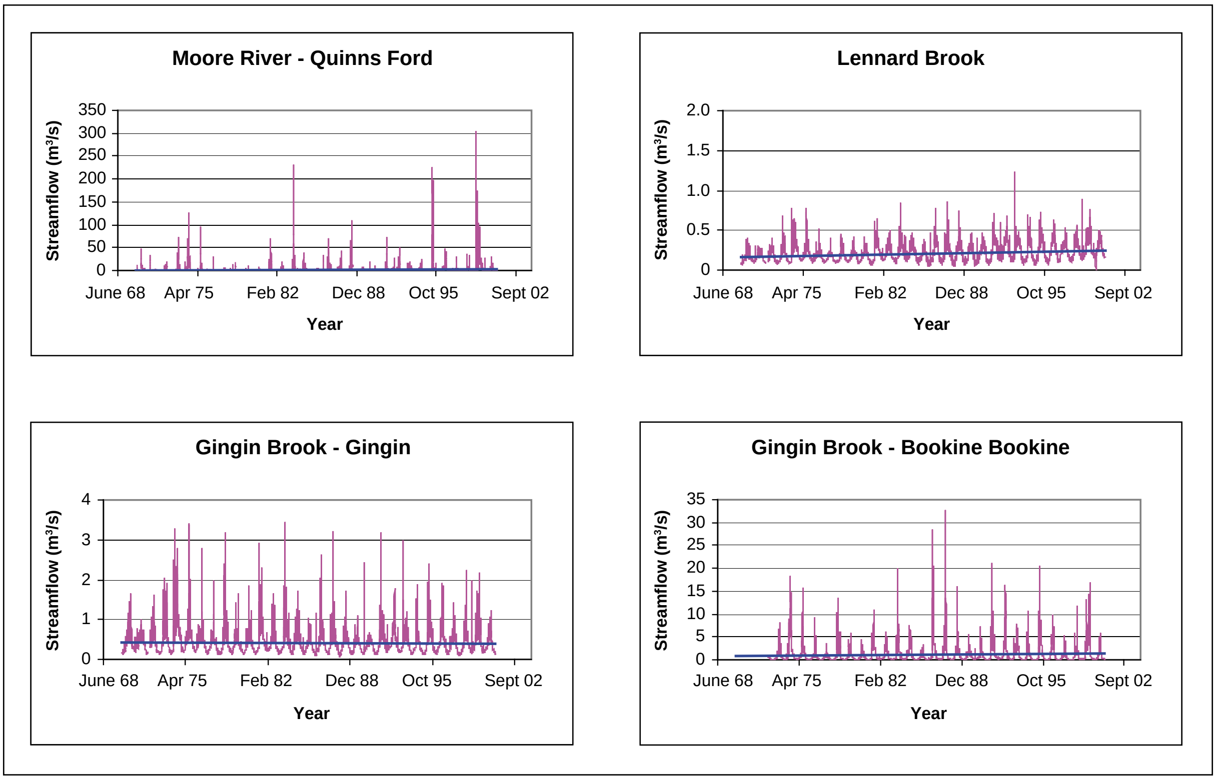


Figure 120 Daily streamflow data for selected drainages in the northern Perth region (blue line represents linear trend)

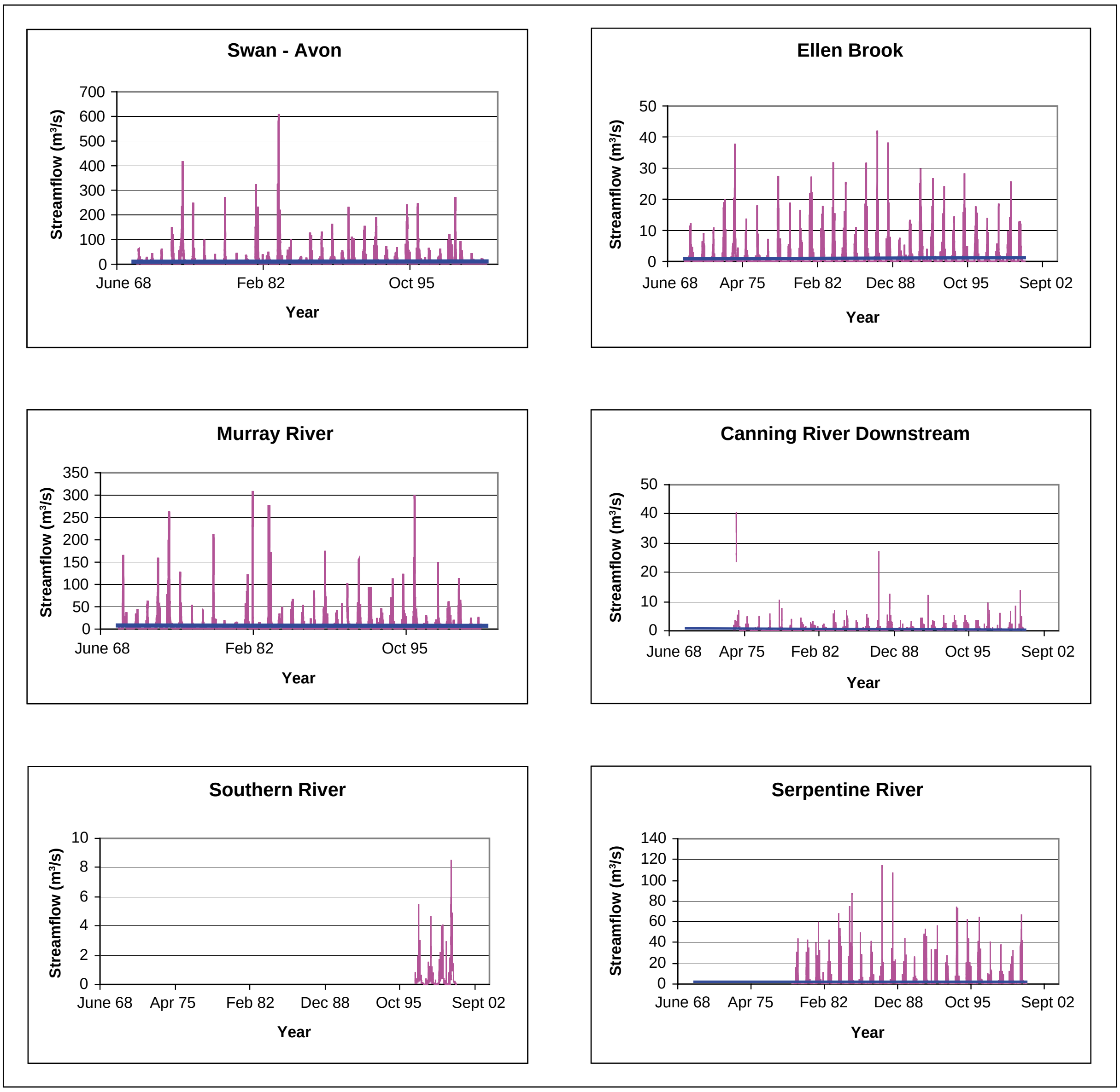


Figure 121 Daily streamflow data for selected drainages in the central and southern Perth regions (blue line represents linear trend)

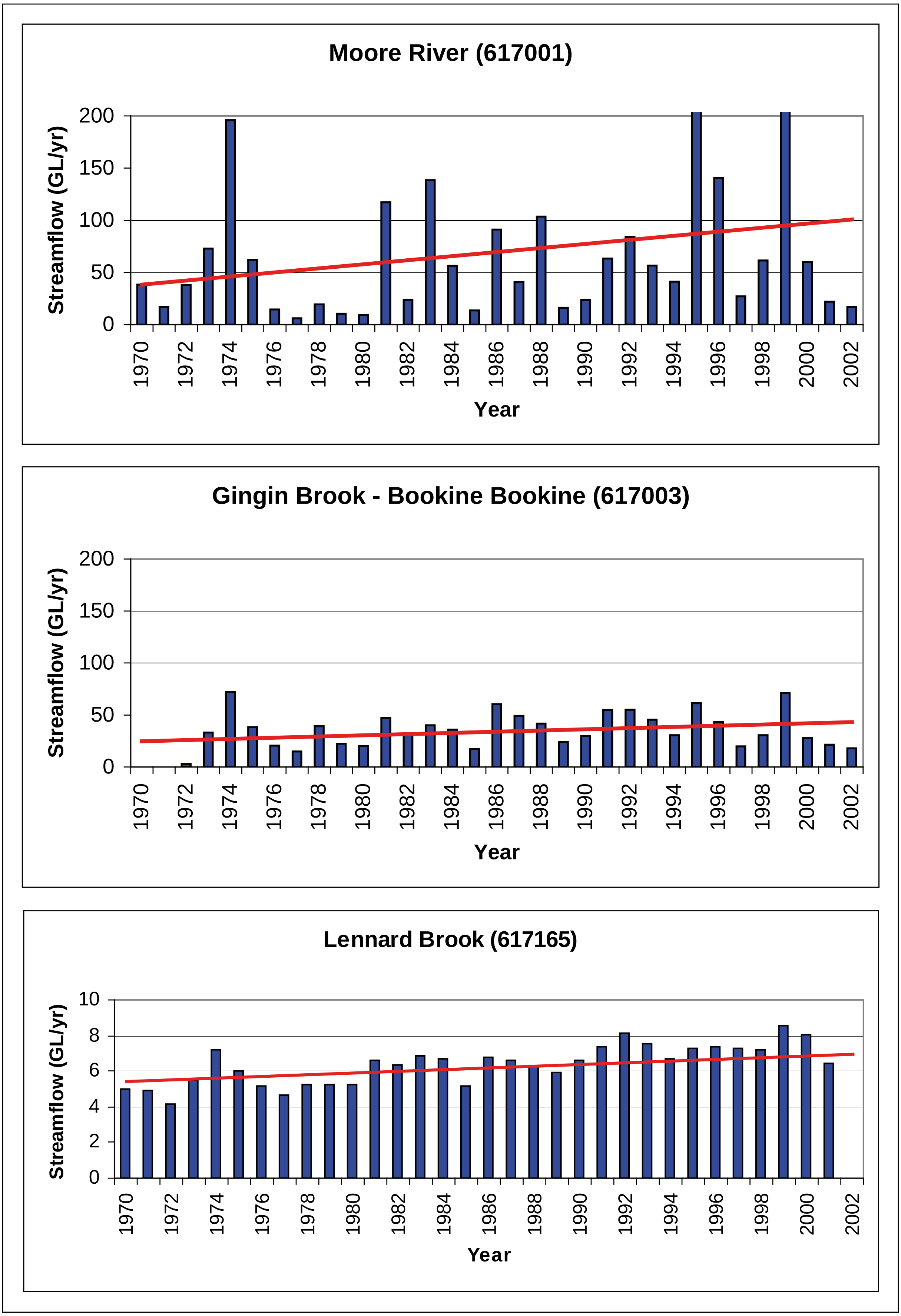


Figure 122 Annual streamflow of drainage in the northern Perth region (red line represents linear trend)

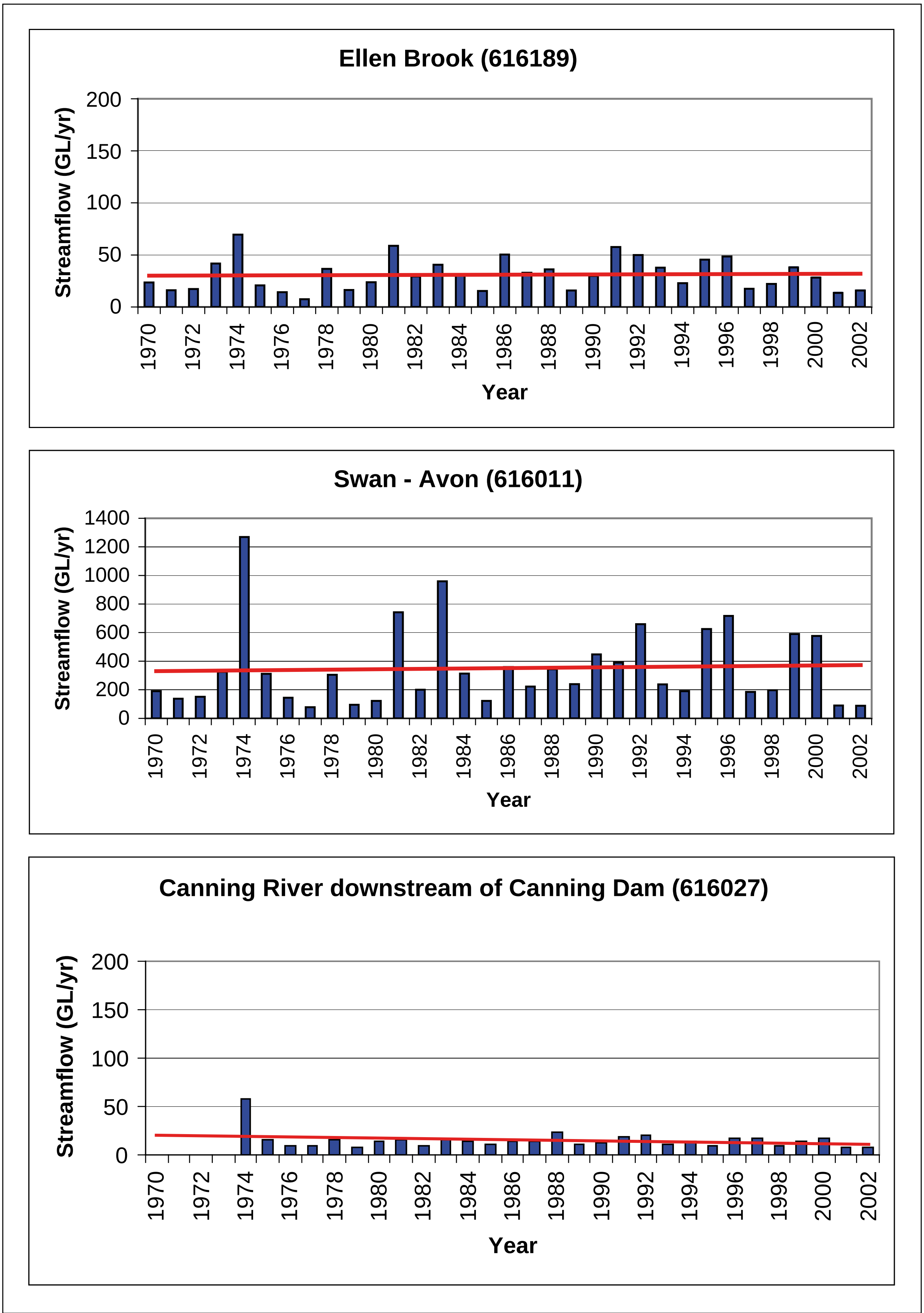


Figure 123 Annual streamflow of drainage in the central Perth region (red line represents linear trend)

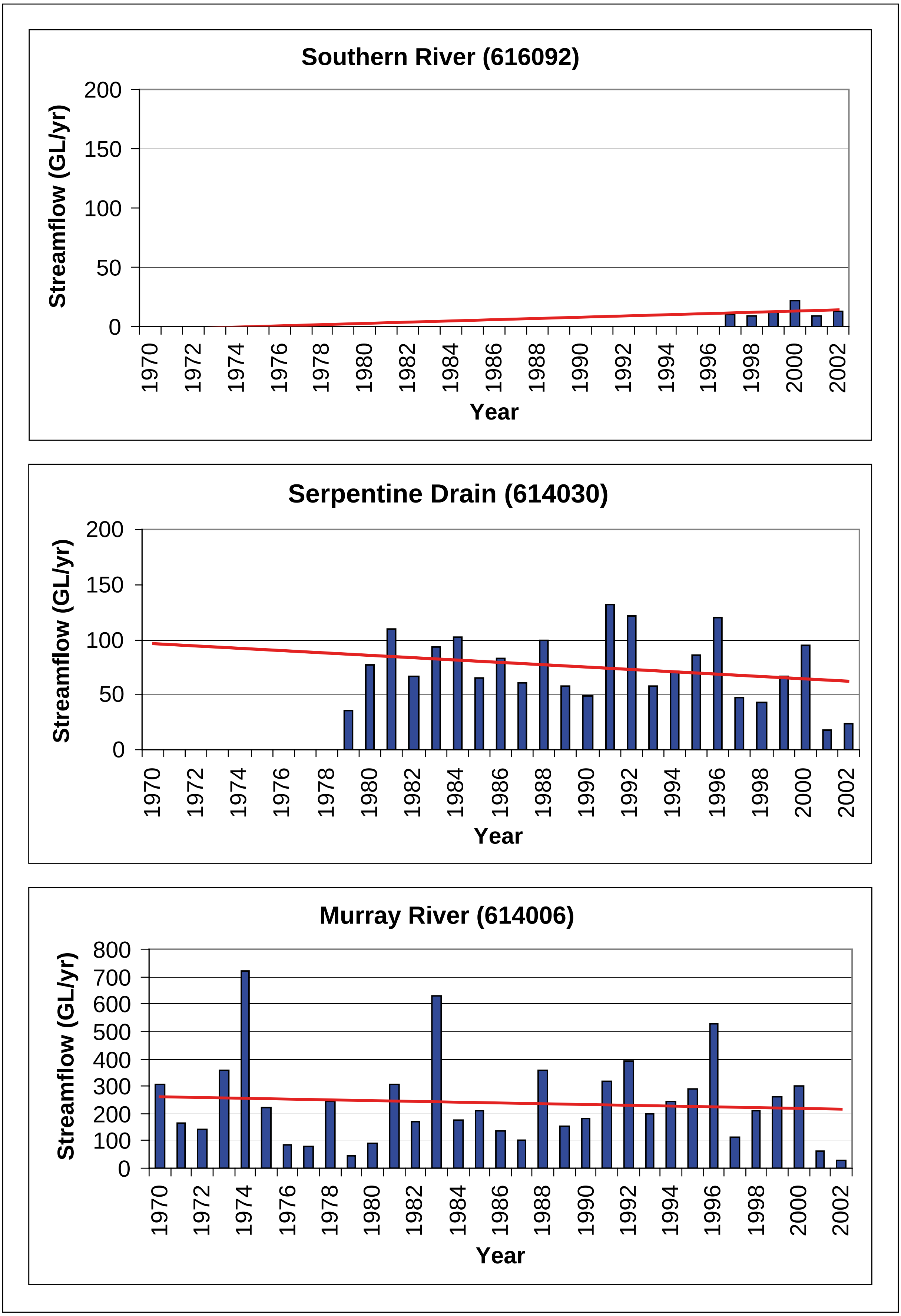


Figure 124 Annual streamflow of drainage in the southern Perth region (red line represents linear trend)

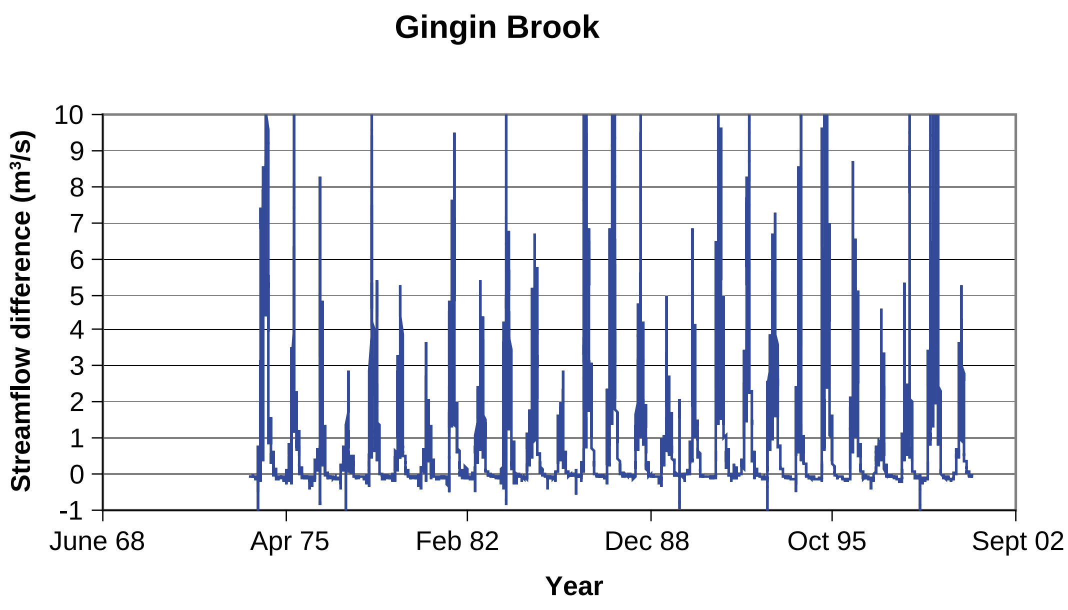


Figure 125 Gingin Brook: streamflow difference between the two gauging stations

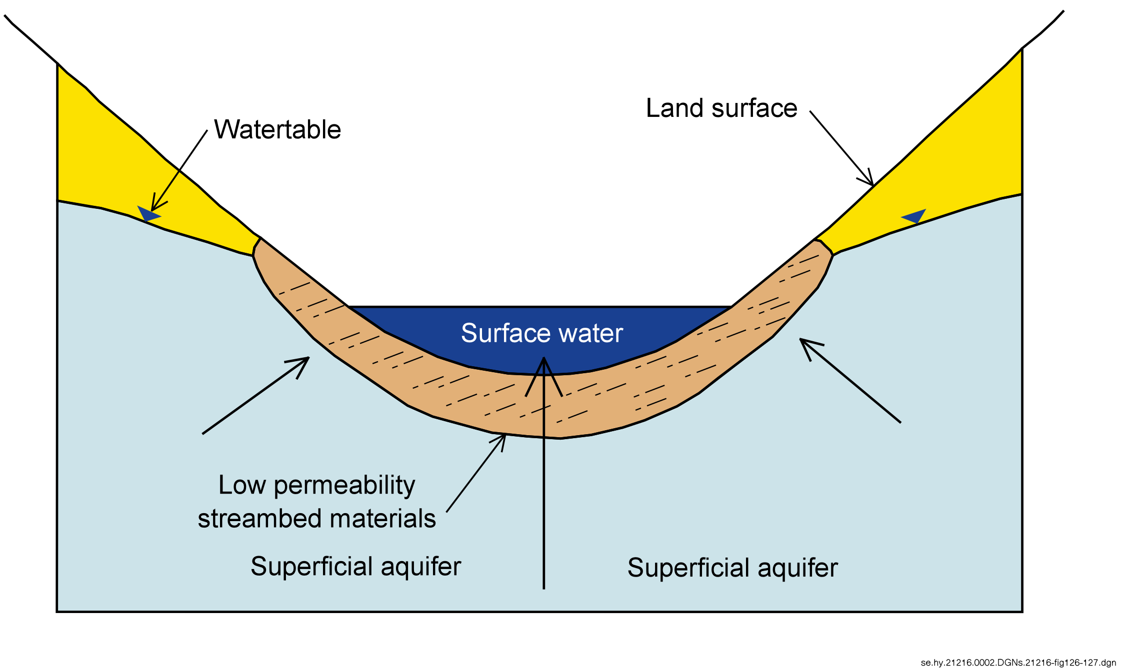


Figure 126 Surface water-groundwater interaction: conceptual model 1 – Groundwater discharge to drain

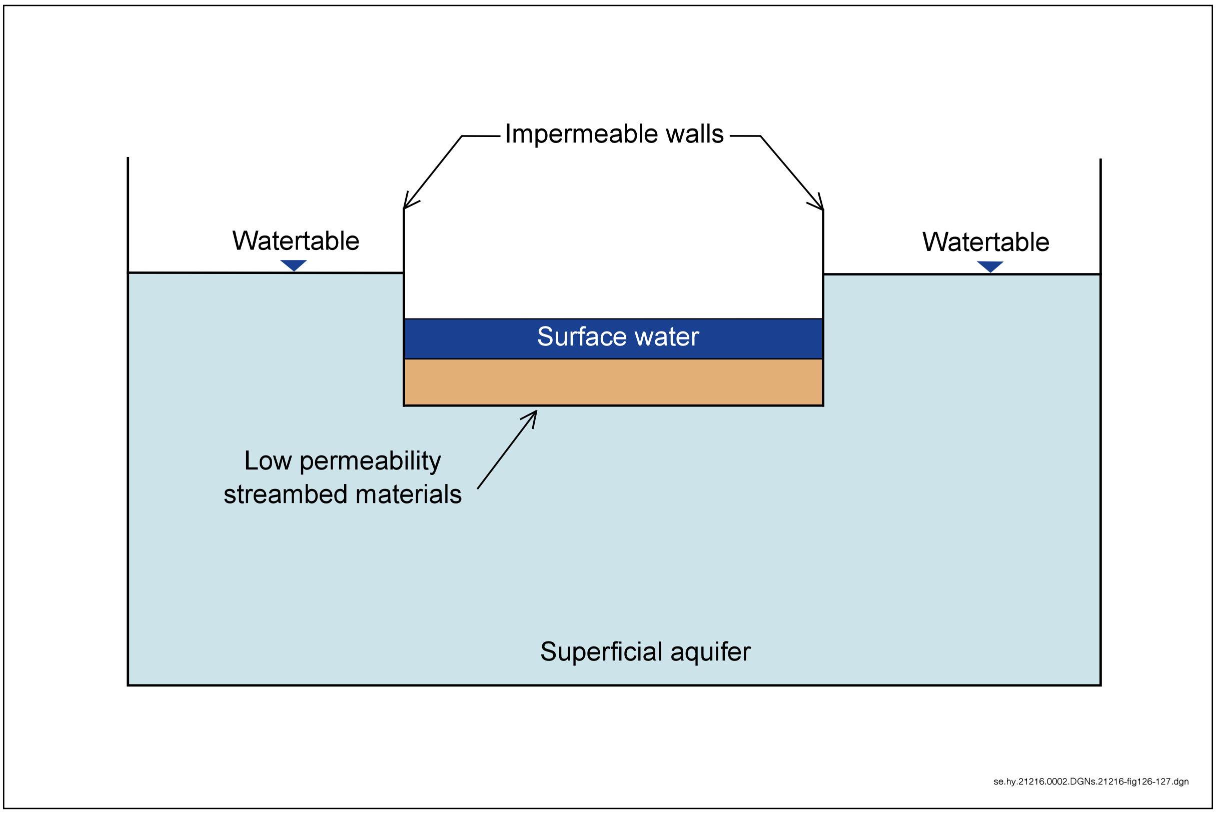


Figure 127 Surface water-groundwater interaction: conceptual model 1 – Drainage Package in Modflow (after McDonald and Harbaugh, 1988)

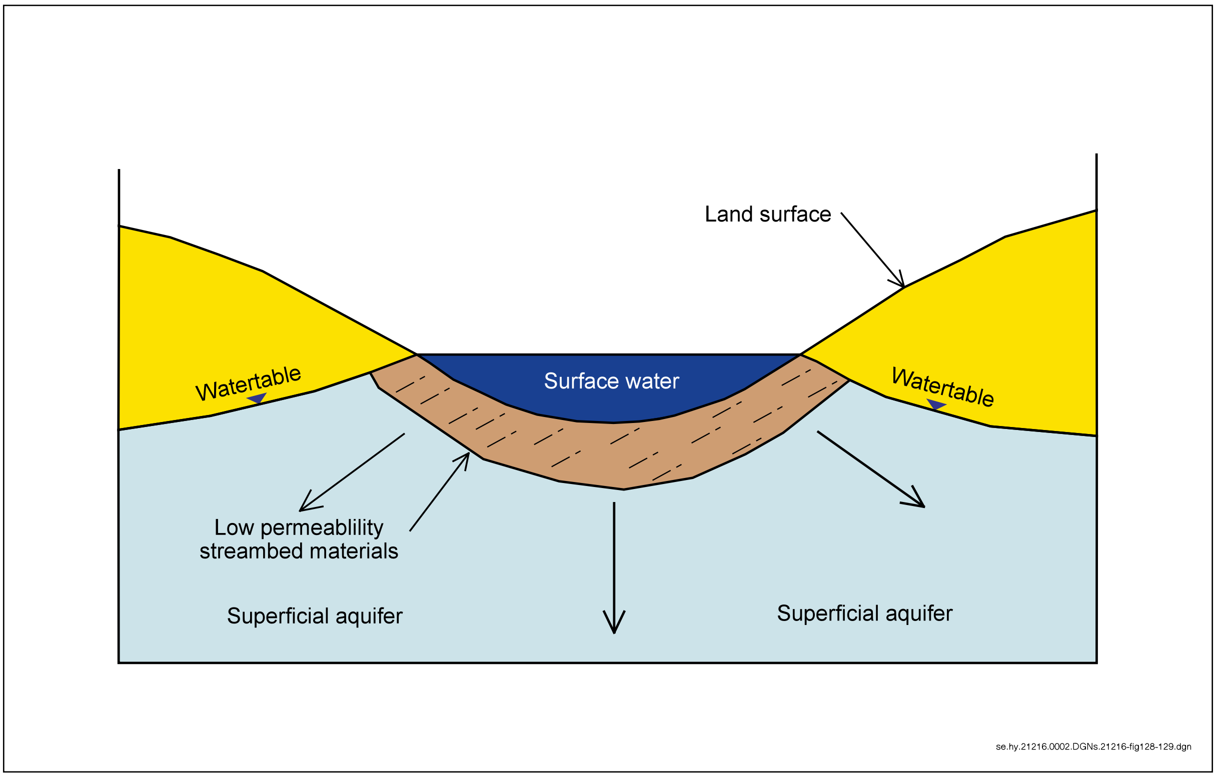


Figure 128 Surface water-groundwater interaction: conceptual model 2 – Groundwater recharged from drain

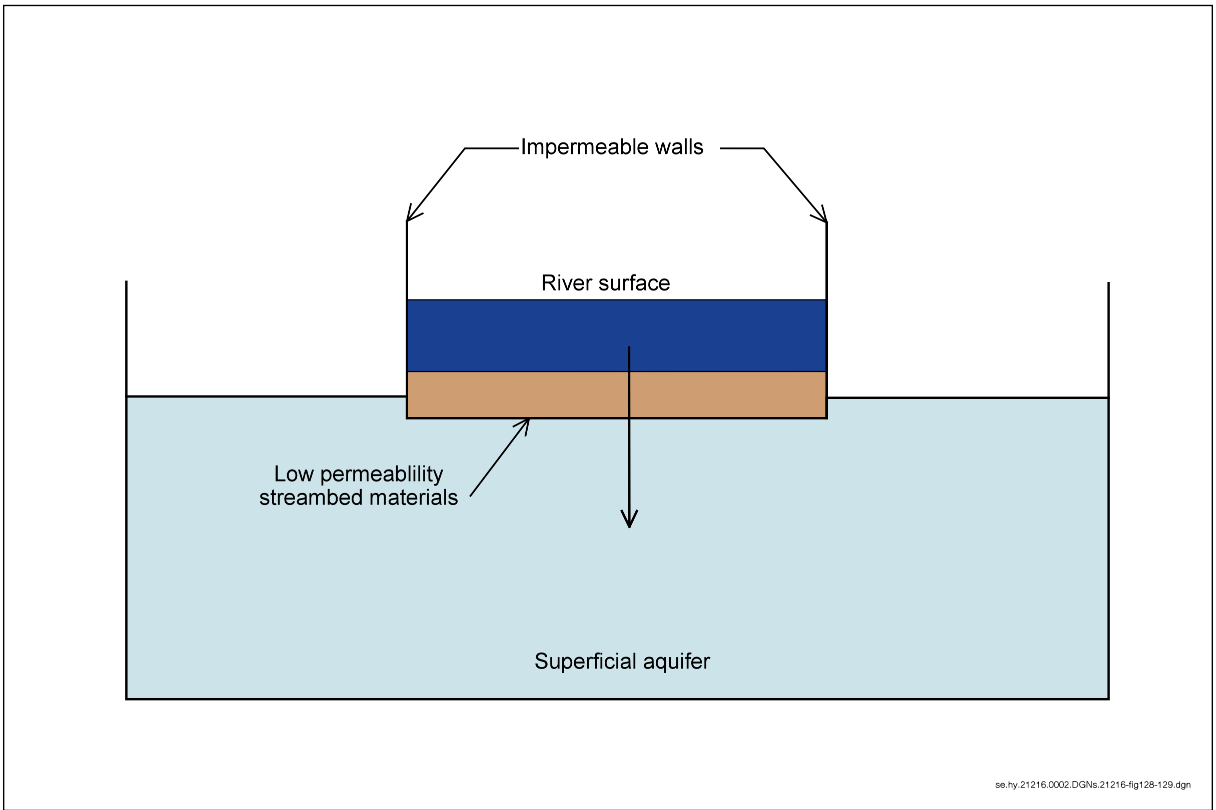


Figure 129 Surface water-groundwater interaction: conceptual model 2 – Recommended improvement in future studies

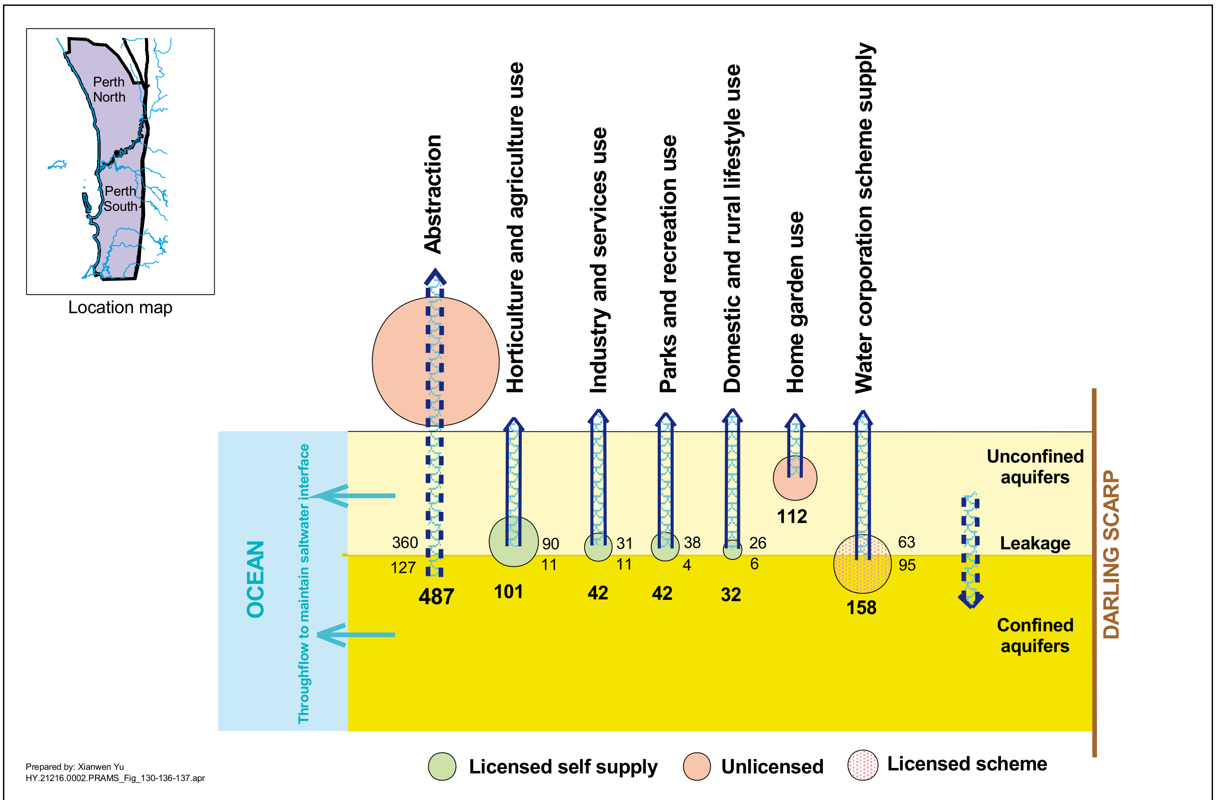


Figure 130 Perth Groundwater Region 2004: groundwater use (GL/yr)

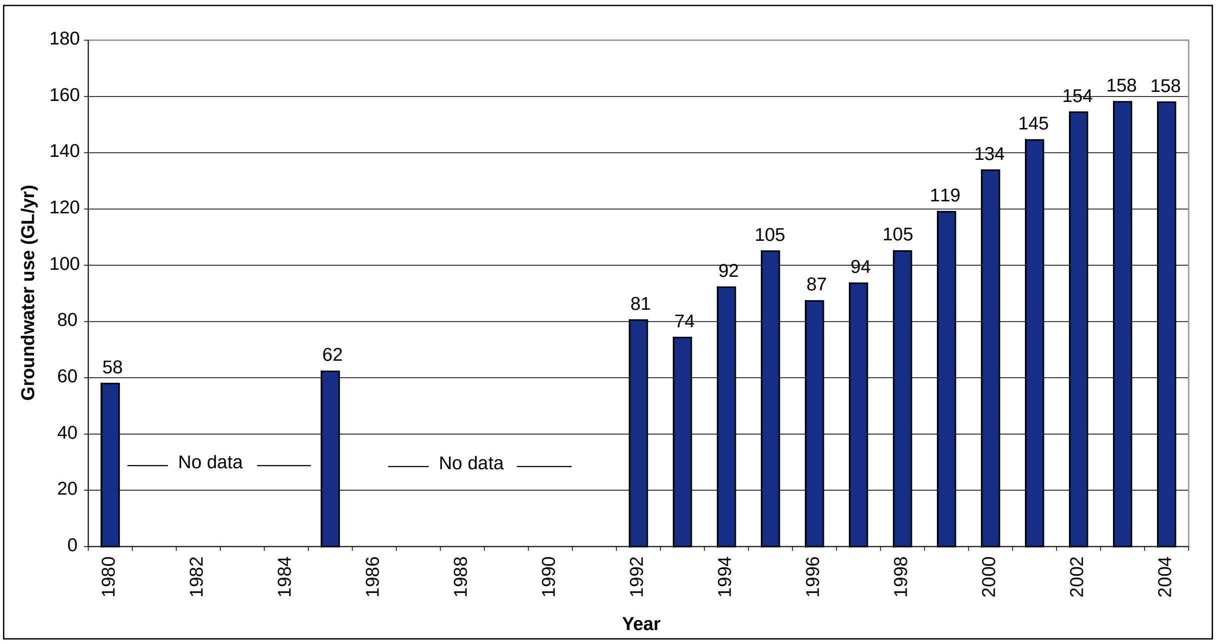


Figure 131 Estimated historical scheme groundwater supply by Water Corporation

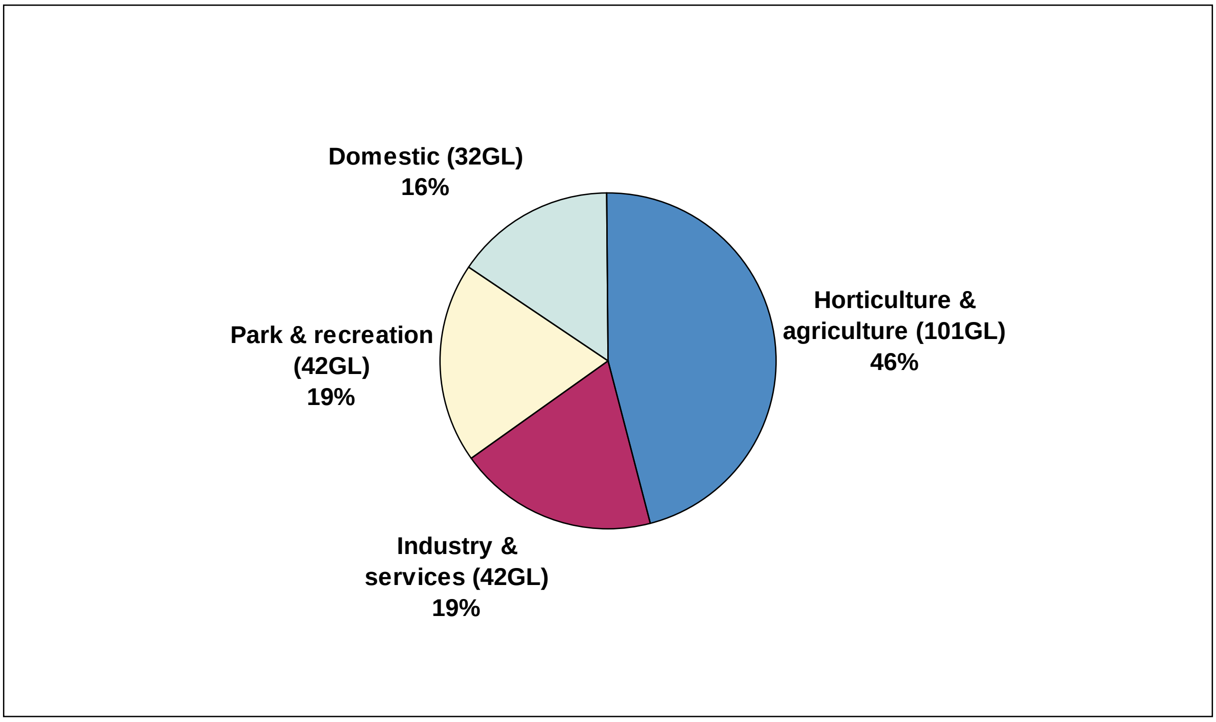


Figure 132 Annual self-supply by licensed private bores: major water use types (2004)

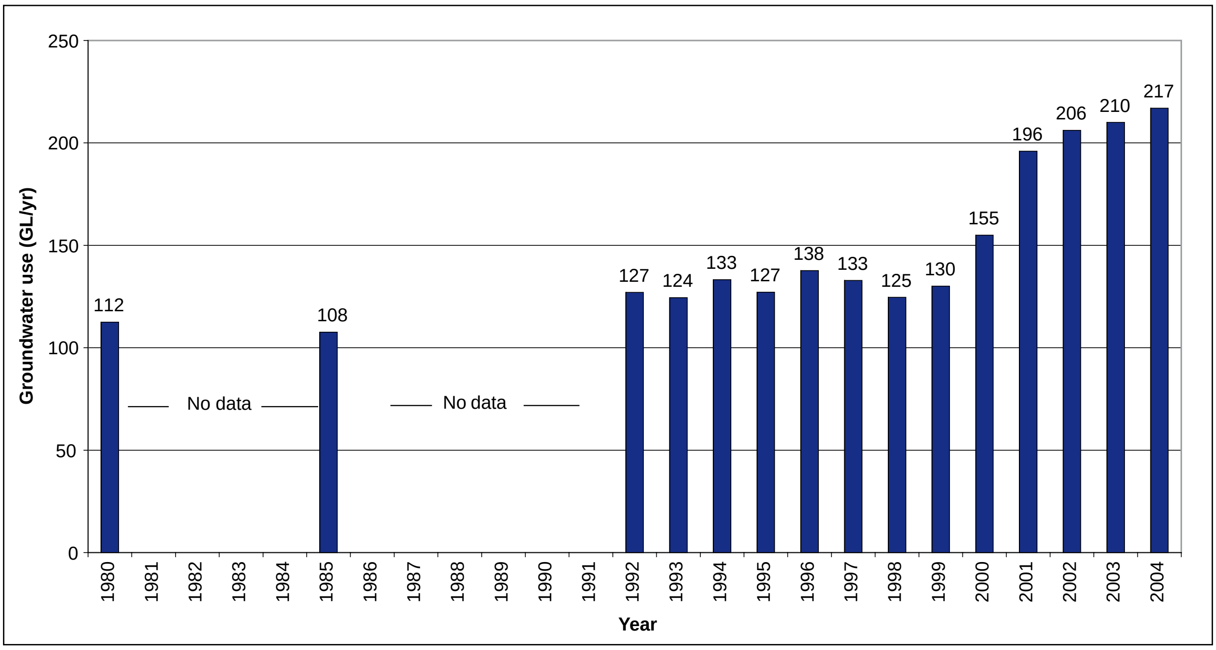


Figure 133 Estimated historical groundwater self-supply by licensed private bores

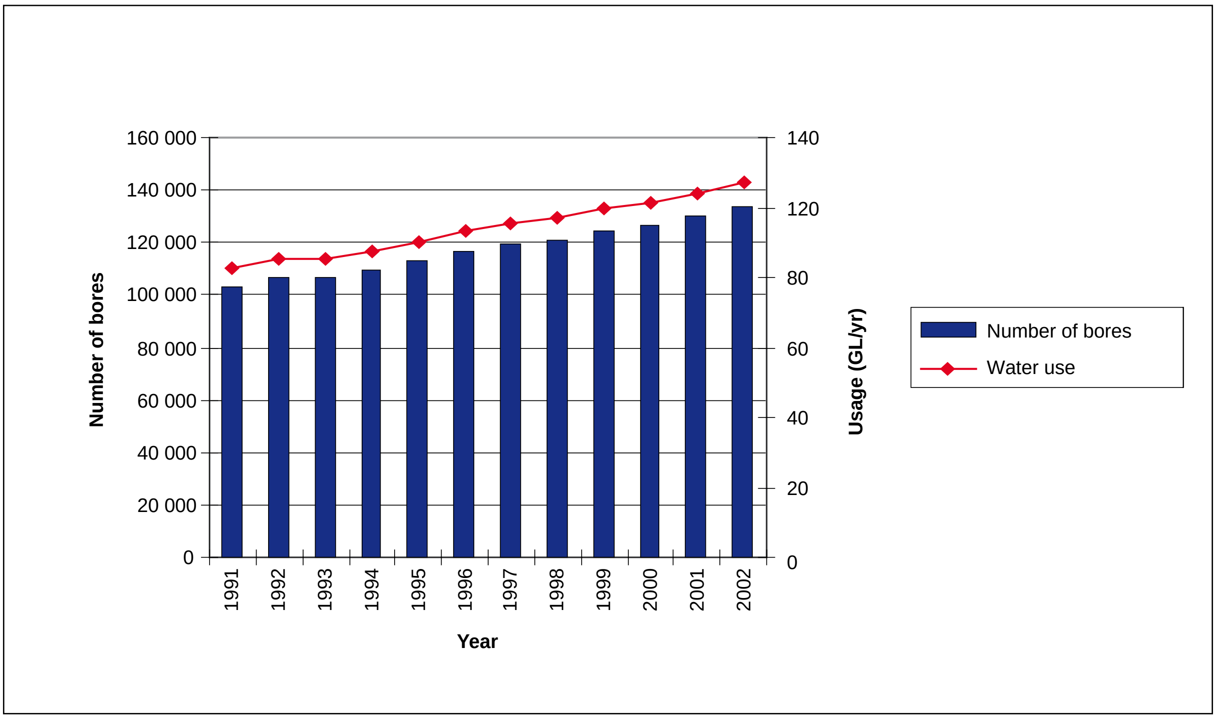


Figure 134 Unlicensed garden bores: estimated total bore number and usage

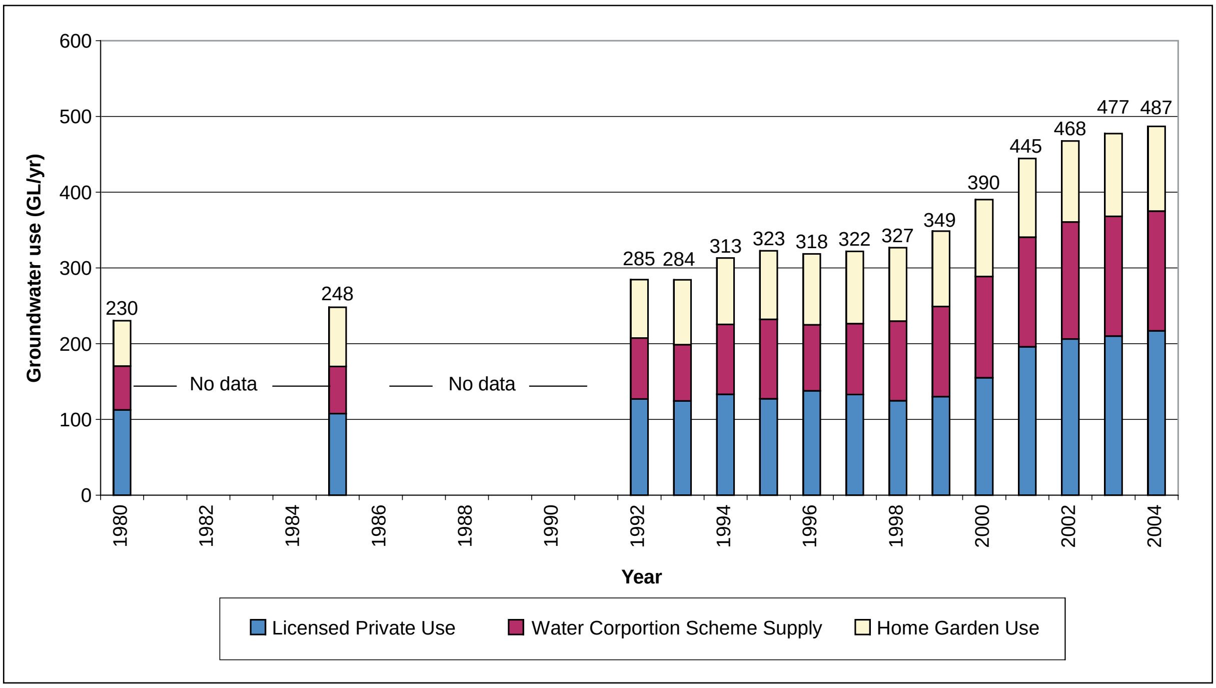


Figure 135 Estimated historical total groundwater use in the Perth Region

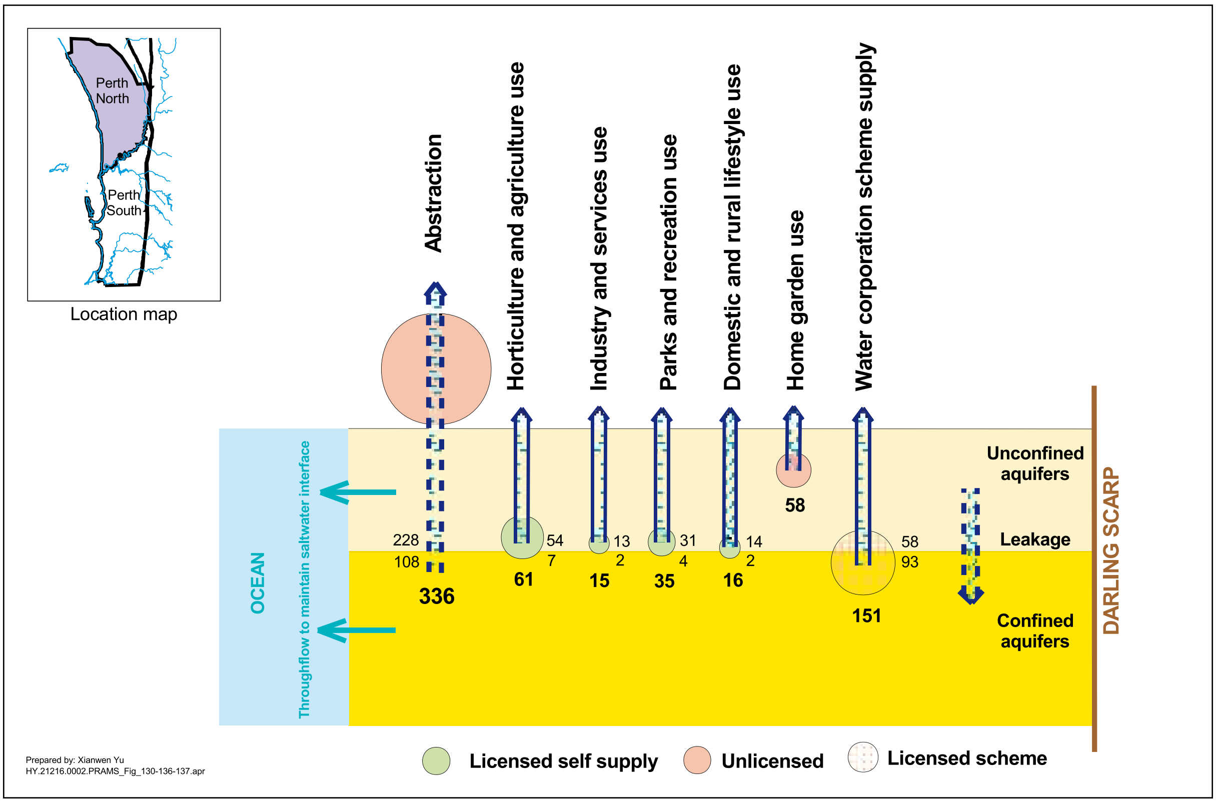


Figure 136 Gnangara Mound (Perth north): 2004 groundwater use (GL/yr)

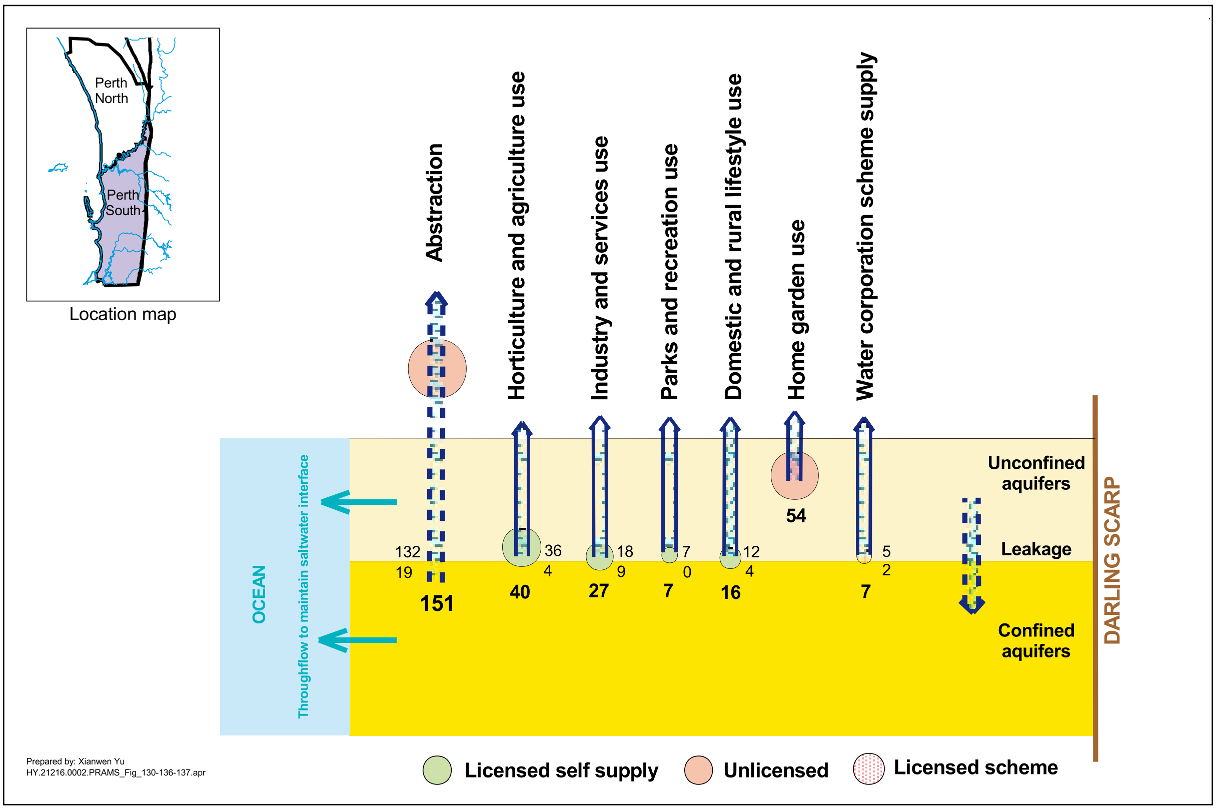


Figure 137 Jandakot Mound (Perth south): 2004 groundwater use (GL/yr)

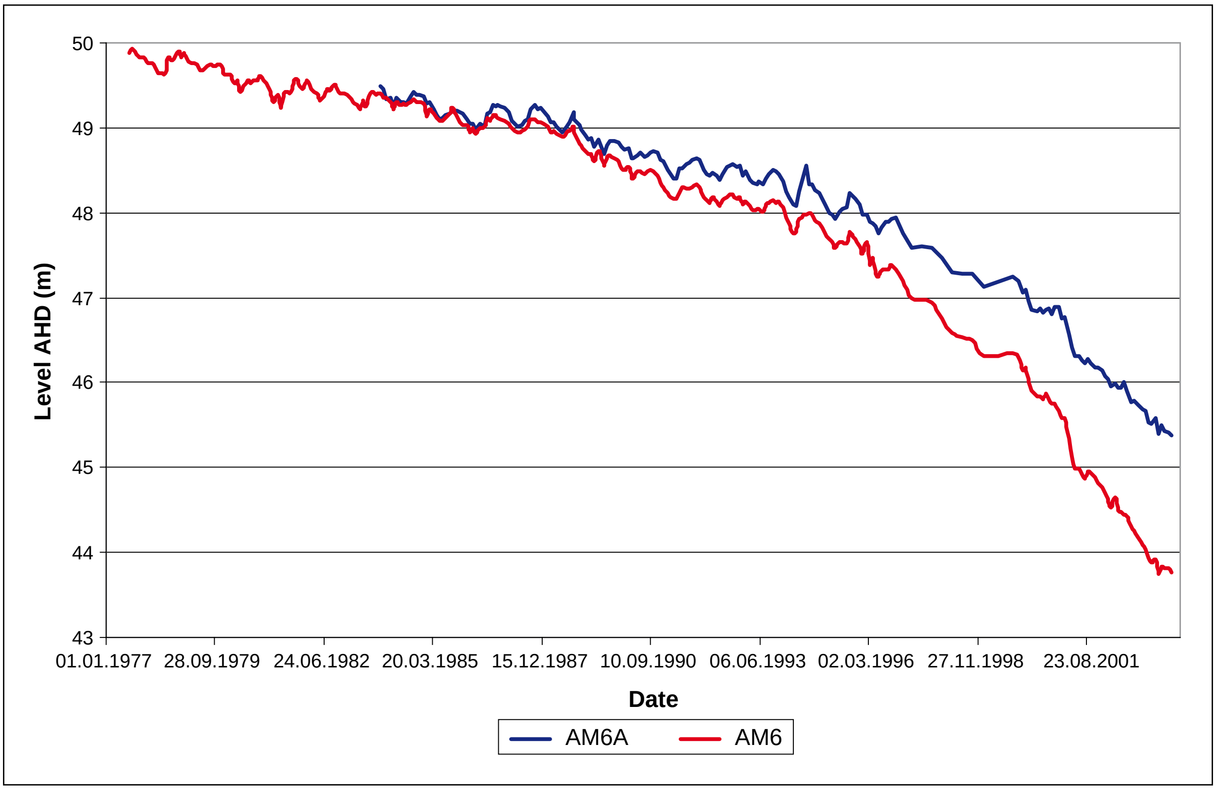


Figure 138 Hydrographs showing significant water level decline in the Leederville (AM6A) and Yarragadee (AM6) aquifers near Gingin Brook and the Gingin Scarp

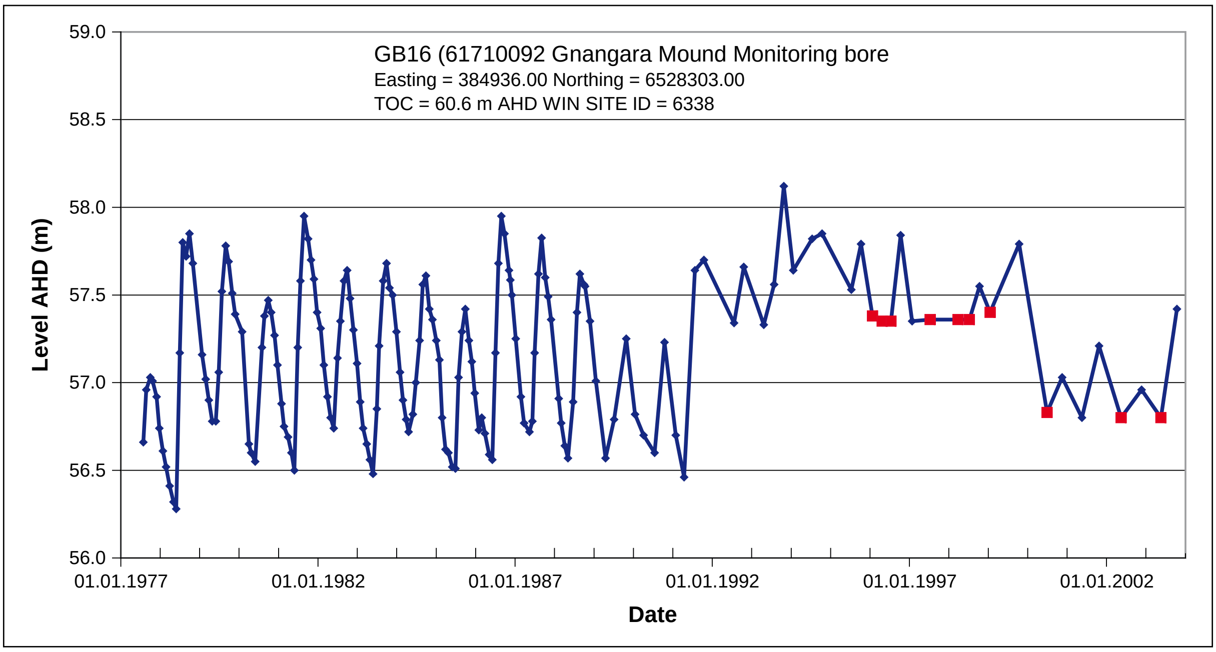


Figure 139 Groundwater hydrographs in the superficial aquifer showing a stable trend near Gingin Brook and the Gingin Scarp

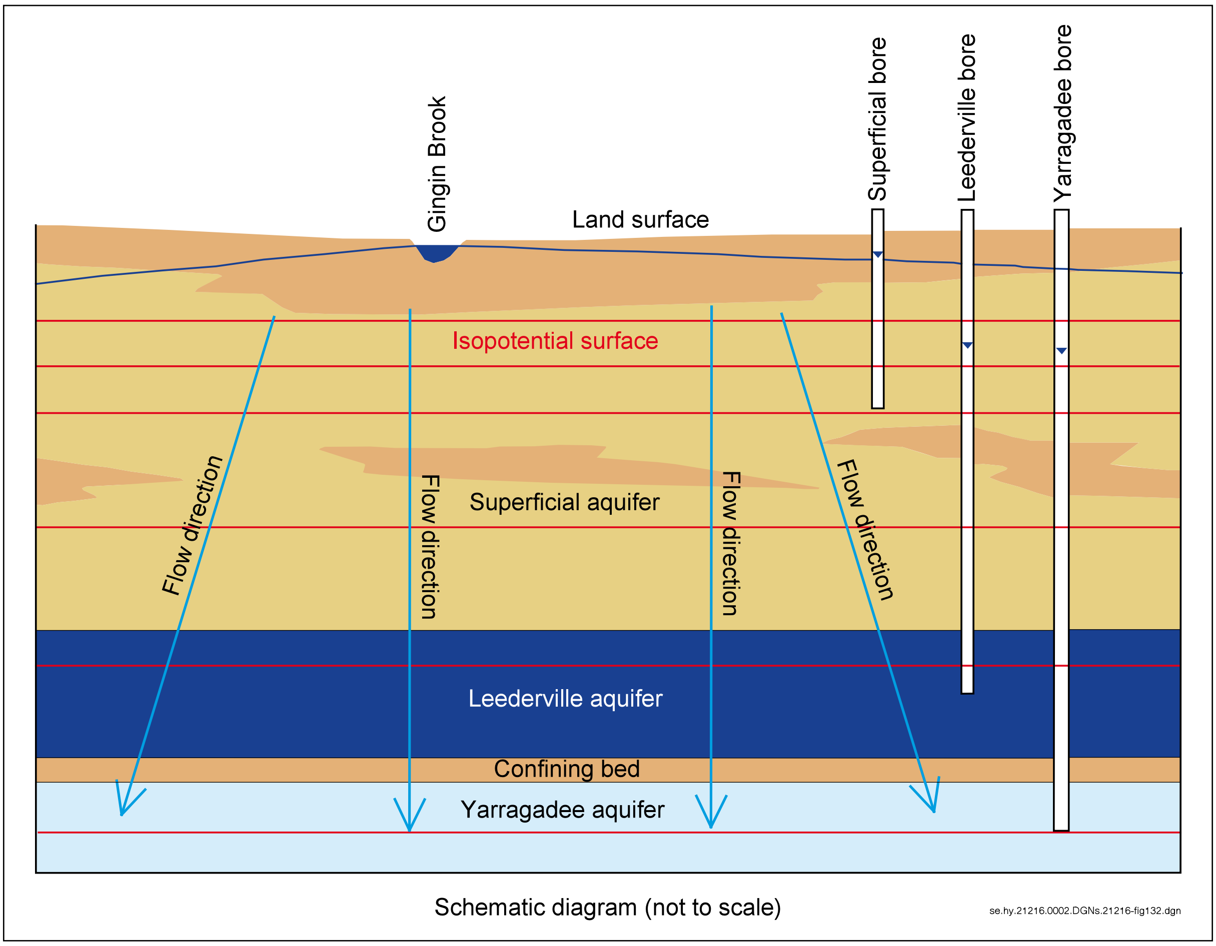


Figure 140 Gingin Brook: schematic diagram showing that Gingin Brook and surrounding wetlands control the watertable in the superficial aquifer and cause significant hydraulic gradients between the aquifers

Appendix B Tables

Table 1 Stratigraphic data from artesian monitoring and selected bores

Bore ID	Ground level (m AHD)	Easting	Northing	Base of formation below ground level (m)																					
						Tk							Kco			Kwl					Kp				
				TQ	Tr	Tkm		Tkc	Kcl	Kcp	Kcg	Kcm	Kcom	Kcok	Kcoh	Kwlp	Kwlw	Kwlm	Kws	Kwg	Kpc	Kps	Kpo	Jy	Jc
AM1	53	356924	6531829	99	-	-	-	-	157	-	167	218	-	-	-	222	499	505	517	-	680	-	-	-	-
AM2	36	365646	6529649	61	-	-	-	-	96	-	120	123	-	210	-	220	605	775	803	829	-	-	-	881	-
AM3	27	367173	6535521	39	-	-	-	-	44	-	60	70	-	164	-	167	606	729	-	-	-	-	-	-	-
AM4	50	383790	6535459	41	-	-	-	-	-	-	-	-	-	-	-	92	143	200	204	332	-	-	-	549	-
AM5	52	375480	6527971	54	-	-	-	-	-	-	-	-	-	-	-	-	242	277	-	-	-	-	-	302	-
AM6	64	386985	6529614	28	-	-	-	-	-	-	-	-	-	-	-	-	80	-	-	-	-	-	-	300	-
AM7	102	398727	6527718	3	-	-	-	-	-	-	-	-	-	20	-	168	306	-	-	-	721	-	-	-	-
AM8	52	368988	6522790	75	-	-	162	-	183	-	226	-	-	340	-	371	810	-	-	-	-	-	-	-	-
AM9	59	380917	6522375	58	-	-	-	-	-	-	-	-	-	-	-	203	303	-	-	-	-	-	-	-	-
AM10	69	392249	6521848	51	-	-	-	-	-	-	-	-	-	-	-	93	111	135	-	-	-	-	190	298	-
AM11	190	406614	6525106	3	-	-	-	-	-	76	93	113	-	229	270	342	684	714	-	-	-	782	810	-	-
AM12	16	368581	6511653	45	-	-	191	-	208	-	247	256	-	373	-	419	750	838	-	-	-	-	-	-	-
AM13	54	374909	6516946	65	-	-	-	-	-	-	-	-	-	-	-	108	259	323	-	-	-	-	-	798	-
AM14	75	386758	6516658	69	-	-	-	-	-	-	-	-	-	-	-	-	161	170	-	-	-	-	-	810	-
AM15	69	400874	6517429	20	-	-	-	-	-	63	71	81	-	97	-	180	480	497	-	-	784	-	-	-	-
AM17	72	384288	6510078	80	-	-	-	-	-	-	-	-	-	-	-	-	108	199	-	-	-	-	-	301	-
AM18	77	397130	6510141	69	-	-	-	-	-	-	-	-	-	-	-	102	300	-	-	-	-	-	-	-	-
AM18A	60	399959	6510643	37	-	-	-	-	-	51	59	102	-	-	-	143	365	490	-	-	676	-	-	-	-
AM19	69	405304	6507016	27	-	-	-	-	-	-	-	-	-	137	148	194	480	500	-	-	-	675	774	802	-
AM20	29	377567	6500435	56	-	-	-	-	-	-	-	-	-	-	-	68	192	269	312	-	-	-	-	467	-
AM21	59	387307	6503748	60	-	-	-	-	-	-	-	-	-	-	-	-	132	192	218	-	-	-	-	464	-
AM22	82	395222	6501479	64	-	-	-	-	-	-	-	-	-	-	-	153	414	-	-	-	513	576	610	-	-
AM23	29	380419	6493089	57	-	-	-	-	-	-	-	-	-	-	-	84	190	240	304	335	-	-	-	470	-
AM24	50	389763	6491300	55	-	-	-	-	-	66	80	103	-	142	157	223	423	507	798	908	-	-	-	-	-
AM25	73	396157	6494906	63	-	-	-	-	-	78	87	122	-	144	-	150	348	382	-	-	430	474	605	-	-
AM26	37	404955	6497166	24	-	-	-	-	-	57	63	82	-	94	103	-	426	481	-	-	523	662	674	-	-
AM27	34	384680	6483682	67	-	-	-	-	-	-	-	80	-	-	97	118	273	325	389	434	-	-	-	762	-
AM28	53	392620	6485039	58	-	-	-	-	-	144	165	192	-	218	225	292	503	554	625	-	-	-	-	-	-
AM29	48	402291	6491061	54	-	-	-	-	-	122	137	149	-	163	184	300	516	628	-	-	651	753	-	-	-

Table 1 (continued)

Bore ID	Ground level (m AHD)	Easting	Northing	Base of formation below ground level (m)																					
						Tk							Kco			Kwl					Kp				
				TQ	Tr	Tkm		Tkc	Kcl	Kcp	Kcg	Kcm	Kcom	Kcok	Kcoh	Kwlp	Kwlw	Kwlm	Kws	Kwg	Kpc	Kps	Kpo	Jy	Jc
AM30	50	402431	6482066	53	-	-	-	-	-	122	129	148	-	168	206	225	500	527	626	-	-	-	-	747	-
AM30Z	39	397699	6478981	34	-	-	-	-	-	-	-	-	199	217	226	330	508	523	565	-	-	-	-	-	-
AM30Y	41	397426	6479756	30	-	-	-	-	-	-	-	-	195	201	210	325	491	512	615	-	-	-	-	855	-
AM31	6	406171	6480712	15	-	-	-	-	-	-	-	-	-	91	98	103	326	406	441	-	-	-	-	800	-
AM32	13	383037	6473764	54	-	-	209	232	-	-	-	-	-	-	-	-	-	-	294	363	-	-	-	404	-
AM33A	7	385155	6477330	34	-	52	-	-	-	-	-	-	105	109	117	126	264	309	376	437	-	-	-	533	-
AM34A	41	394664	6474341	46	-	-	-	-	-	-	-	-	-	116	214	270	495	540	638	735	-	-	-	-	-
AM35A	17	403601	6475592	20	-	-	-	-	-	-	-	-	48	134	144	198	450	495	561	-	-	-	-	649	-
AM36	16	387766	6470299	36	-	-	-	-	-	-	-	55	-	88	114	144	276	297	398	465	-	-	-	616	-
AM37A	21	398469	6469322	29	-	-	-	-	-	-	-	-	142	174	205	336	540	601	681	732	-	-	-	804	-
AM38A	11	404921	6468931	18	-	-	-	-	-	-	-	-	-	30	62	137	335	381	420	550	-	-	-	-	-
AM39Z	8	384742	6461214	32	-	122	558	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	595	-
AM40	23	394744	6460282	33	-	166	326	383	-	-	-	-	-	-	-	-	493	517	610	705	-	-	-	741	-
AM41	21	404135	6460863	23	-	-	62	-	-	-	-	-	-	69	94	-	312	355	399	419	-	-	-	505	-
AM42	29	388123	6452372	28	-	-	-	-	-	-	-	-	-	167	177	186	333	399	499	600	-	-	-	-	-
AM43A	29	393965	6450856	48	-	-	-	-	-	-	-	-	-	175	180	275	369	506	558	647	-	-	-	794	-
AM44	6	403563	6455430	12	-	-	-	-	-	-	-	-	-	28	35	132	186	280	333	-	-	-	-	-	-
AM45	39	387831	6443556	63	-	-	-	-	-	-	-	-	-	181	-	222	338	396	409	-	-	-	-	-	-
AM46	28	393953	6444474	49	-	-	-	-	-	-	-	-	-	88	116	216	360	420	475	581	-	-	-	801	-
AM47	27	398111	6444063	48	-	-	-	-	-	-	-	-	-	55	66	145	235	302	340	405	-	-	-	742	-
AM48	24	402841	6446614	27	-	-	-	-	-	-	-	-	-	-	-	-	197	320	-	357	-	-	-	618	-
AM49	36	391636	6438965	54	-	-	-	-	-	-	-	-	-	104	117	192	300	375	432	449	-	-	-	554	-
AM50	16	399219	6434287	28	-	-	-	-	-	-	-	-	-	-	-	37	123	209	241	-	-	-	-	354	-
AM50Y	31	403609	6432449	27	-	-	-	-	-	-	-	-	-	-	-	100	-	-	-	-	-	-	-	-	301
AM50Z	21	401283	6435204	13	-	-	-	-	-	-	-	-	-	-	-	91	-	-	-	-	-	-	-	-	183
AM51	27	403687	6439011	15	-	-	-	-	-	-	-	-	-	-	-	44	57	128	-	-	-	-	-	-	421
AM52	4	383439	6434823	28	-	-	-	-	-	-	-	-	-	-	-	95	204	243	378	481	-	-	-	-	-
AM52Y	6	374326	6441206	34	-	-	-	-	-	-	-	-	-	164	174	238	252	288	331	435	-	-	-	-	-
AM52Z	4	376115	6433422	34	94	-	186	-	-	-	-	-	-	223	238	-	-	302	361	-	-	-	-	-	387

Table 1 (continued)

Bore ID	Ground level (m AHD)	Easting	Northing	Base of formation below ground level (m)																					
						Tk							Kco			Kwl					Kp				
				TQ	Tr	Tkm		Tkc	Kcl	Kcp	Kcg	Kcm	Kcom	Kcok	Kcoh	Kwlp	Kwlw	Kwlm	Kws	Kwg	Kpc	Kps	Kpo	Jy	Jc
AM53A	22	391439	6433324	42	-	-	-	-	-	-	-	-	-	63	-	141	264	355	393	523	-	-	-	551	-
AM54	5	381972	6426982	28	138	-	-	-	-	-	-	-	-	-	-	-	194	243	331	392	-	-	-	-	448
AM55	7	392475	6423101	18	-	-	-	-	-	-	-	-	-	-	-	75	120	245	305	339	-	-	-	401	-
AM56	34	404176	6425908	15	-	-	-	-	-	-	-	-	-	-	-	-	47	119	-	-	-	-	-	-	353
AM57	2	380392	6417422	37	136	-	-	-	-	-	-	-	-	-	-	-	157	283	326	405	-	-	-	-	801
AM58	9	387338	6415685	24	101	-	-	-	-	-	-	-	-	-	-	-	140	246	288	345	-	-	-	-	746
AM59	8	392454	6417800	14	-	-	-	-	-	-	-	-	-	-	-	28	128	229	263	333	-	-	-	796	-
AM60	16	397359	6416394	12	-	-	-	-	-	-	-	-	-	-	-	-	78	160	185	213	-	-	-	810	-
AM61	37	402244	6416861	16	-	-	-	-	-	-	-	-	-	-	-	-	39	105	-	-	-	-	-	-	802
AM62	8	387727	6410862	17	51	-	-	-	-	-	-	-	-	-	-	-	70	195	237	276	-	-	-	-	386
AM63	22	395615	6410203	15	-	-	-	-	-	-	-	-	-	-	-	25	99	216	240	-	-	-	-	349	-
AM64	55	403825	6410003	13	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	357
AM65	2	387523	6403674	9	57	-	-	-	-	-	-	-	-	-	-	-	69	188	208	-	-	-	-	-	363
AM66	21	397363	6403772	10	-	-	-	-	-	-	-	-	-	-	-	-	36	142	149	188	-	-	-	384	-
AM67	11	382835	6402182	21	44	-	-	-	-	-	-	-	-	-	-	-	96	186	246	-	-	-	-	-	375
AM68	9	390782	6398413	8	58	-	-	-	-	-	-	-	-	-	-	-	80	176	203	287	-	-	-	-	327
AM69	41	403632	6402890	2	-	-	-	-	-	-	-	-	-	-	-	-	-	60	-	-	-	-	-	-	417
AM70	21	399256	6397116	4	-	-	-	-	-	-	-	-	-	-	-	-	-	103	-	-	-	-	-	-	505
Miscellaneous bores (onshore)																									
P3	62	390330	6496632	58	-	-	-	-	-	-	-	-	-	-	-	-	271	308	360	450	-	-	-	542	-
P4	71	384498	6497757	84	-	-	-	-	-	-	-	-	-	-	-	-	256	297	377	-	-	-	-	519	-
P6	6	376732	6494433	39	-	-	-	-	-	-	-	-	-	-	-	-	194	258	341	-	-	-	-	604	-
P7	67	391979	6503665	6	-	-	-	-	-	-	-	-	-	9	26	-	256	277	350	-	555	-	-	-	-
W1	91	387603	6486020	113	-	-	-	-	-	128	144	174	-	204	234	299	526	612	854	906	-	-	-	-	-
W257	55	391514	6489660	63	-	-	-	-	-	115	124	128	-	140	171	247	435	580	815	915	-	-	-	1108	-
M1	42	393720	6476397	52	-	-	-	-	-	-	-	58	-	122	197	238	451	514	579	716	-	-	-	-	-
M55	32	398039	6476132	35	-	-	-	-	-	-	-	-	183	200	208	283	450	500	-	-	-	-	-	-	-
M285	35	402314	6479810	39	-	-	-	-	-	71	-	90	118	143	183	219	458	516	526	-	-	-	-	-	-

Table 1 (continued)

Bore ID	Ground level (m AHD)	Easting	Northing	Base of formation below ground level (m)																					
						Tk							Kco			Kwl					Kp				
				TQ	Tr	Tkm		Tkc	Kcl	Kcp	Kcg	Kcm	Kcom	Kcok	Kcoh	Kwlp	Kwlw	Kwlm	Kws	Kwg	Kpc	Kps	Kpo	Jy	Jc
M305	45	393971	6481639	49	-	-	-	-	-	-	-	-	100	174	201	263	463	488	-	-	-	-	-	-	-
M345	46	398053	6481679	47	-	-	-	-	-	-	-	-	188	206	-	238	516	-	-	-	-	-	-	-	-
BP1	13	383919	6467519	49	-	-	108	-	-	-	-	-	-	116	122	174	201	253	293	436	-	-	-	615	-
YSC1	26	371966	6510171	55	-	-	-	-	-	-	75	-	-	158	-	210	345	362	448	504	-	-	-	-	-
Y2	14	392399	6469189	34	-	-	-	-	-	-	-	-	56	171	201	256	439	488	552	732	-	-	-	-	-
J45	31	396015	6441298	52	-	-	-	-	-	-	-	-	-	91	129	207	285	396	434	-	-	-	-	-	-
J105	28	397076	6445591	42	-	-	-	-	-	-	-	-	-	60	88	176	268	367	400	-	-	-	-	-	-
GB1	117	401258	6530836	14	-	-	-	-	-	18	23	-	-	100	-	184	316	-	-	-	-	-	-	-	-
GB2	58	366379	6533124	46	-	-	-	-	-	-	-	-	-	-	-	97	152	168	-	-	-	-	-	509	-
GB3	31	373194	6533955	34	-	-	-	-	-	-	-	-	-	-	-	40	235	360	376	405	-	-	-	719	-
GB4	9	362041	6534075	45	-	-	-	-	53	-	66	86	-	165	-	175	535	-	-	-	-	-	-	-	-
GB5	103	395149	6531407	2	-	-	-	-	-	-	-	-	-	-	-	18	82	-	-	-	380	451	514	517	-
QZ35	31	376112	6498639	20	-	-	-	-	-	-	-	-	-	72	-	79	227	238	-	-	-	-	-	-	-
QA25	25	377613	6495588	23	-	-	-	-	-	-	-	-	-	63	-	70	182	221	-	-	-	-	-	-	-
QO25	18	381036	6491169	45	-	-	-	-	-	-	-	74	-	100	-	117	204	-	-	-	-	-	-	-	-
P97	58	387239	6504749							No data							96	157	205	-	-	-	-	400	-
W7	93	388852	6486230	100	-	-	-	-	-	113	120	140	225	253	-	305	543	560	863	1010	-	-	-	1060	-
W57	59	395058	6489798	66	-	-	-	-	-	86	-	-	149	171	-	204	355	417	635	868	-	-	-	1013	-
MPOOL	2	384500	6455733	43	-	-	-	-	-	-	-	-	-	125	175	198	250	303	405	499	-	-	-	748	-
L5	16	391166	6465067	30	-	-	286	-	-	-	-	-	-	-	-	297	415	452	546	700	-	-	-	942	-
MR17	70	386348	6454708					No data						188	195	-	300	367	490	535	-	-	-	743	-
WT15	59	381999	6488239	86	-	-	-	-	-	-	-	105	-	112	151	165	256	-	-	-	-	-	-	-	-
WT45	32	382924	6481907					No data						-	87	110	237	255	275	-	-	-	-	-	-
WT95	45	383729	6479652					No data						105	-	117	256	270	281	-	-	-	-	-	-
WT97	50	383757	6479704	80	-	-	-	-	-	-	-	-	98	105	-	120	256	305	355	374	-	-	-	440	-
P145	78	387271	6509806	66	-	-	-	-	-	-	-	-	-	-	-	-	141	189	206	-	-	-	-	-	-
P105	71	387193	6506015	66	-	-	-	-	-	-	-	-	-	-	-	-	137	182	198	-	-	-	-	-	-
P65	55	387787	6501978	57	-	-	-	-	-	-	-	-	-	-	-	-	117	-	-	-	-	-	-	-	-
P25	58	389408	6498296	60	-	-	-	-	-	-	-	-	-	-	-	87	202	220	-	-	-	-	-	-	-

Table 1 (continued)

Bore ID	Ground level (m AHD)	Easting	Northing	Base of formation below ground level (m)																					
						Tk								Kco			Kwl					Kp			
				TQ	Tr	Tkm		Tkc	Kcl	Kcp	Kcg	Kcm	Kcom	Kcok	Kcoh	Kwlp	Kwlw	Kwlm	Kws	Kwg	Kpc	Kps	Kpo	Jy	Jc
P17	57	389998	6496339	59	-	-	-	-	-	-	-	-	-	-	-	99	248	294	306	477	-	-	-	589	-
EDW2	60	368139	6550149	69	-	-	-	-	108	-	-	-	-	253	-	294	369	-	-	-	-	-	-	-	-
ATD1	3	387830	6455491	27	-	-	76	-	-	-	-	-	-	129	162	186	327	429	490	573	-	-	-	684	-
ZOO2	10	391947	6461588	30	-	52	308	-	-	-	-	-	-	-	-	-	451	497	576	591	-	-	-	643	-
BSWD	4	395470	6464041	28	-	50	149	-	-	-	-	-	-	-	170	202	-	-	-	-	-	-	-	-	-
SN689	163	405139	6511549	4	-	-	-	-	-	-	-	64	90	215	243	253	-	-	-	-	-	-	-	-	-
SN786	135	384139	6532149	-	-	-	-	-	-	-	-	-	-	-	-	81	135	-	-	-	-	-	-	-	-
KR1	216	394957	6539787	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	303	-	-	-	-
KR5	216	394957	6539787	3	-	-	-	-	-	-	-	25	-	28	67	155	216	-	-	-	220	-	-	-	-
TPK	60	374139	6535349	42	-	-	-	-	-	-	-	-	-	-	-	-	168	-	-	-	-	-	-	-	-
EXP1	200	398039	6540149	2	-	-	-	-	-	-	-	-	22	-	30	50	97	-	-	-	-	-	-	-	-
EXP2	230	397865	6539765	2	-	-	-	-	-	11	19	73	-	88	99	116	155	-	-	-	-	-	-	-	-
GL1A	5	342152	6564300	28	-	-	-	-	59	-	76	-	-	-	-	86	206	236	280	-	-	-	-	996	-
GL2	131	350439	6566450	142	-	-	-	-	169	-	175	200	-	208	-	262	607	856	914	943	-	-	-	1004	-
GL3A	60	358839	6567950	58	-	-	-	-	64	-	81	94	-	143	152	193	490	525	675	708	-	-	-	1007	-
GL4A	78	368289	6566750	74	-	-	-	-	-	-	-	-	-	-	-	129	417	595	667	718	-	-	-	1200	-
GL5A	86	376889	6569400	52	-	-	-	-	-	-	-	-	-	-	-	-	119	184	-	300	-	-	-	1200	-
GL6	129	383839	6571350	2	-	-	-	-	-	-	-	-	-	-	-	12	58	101	-	-	355	458	540	974	-
GL7	146	394489	6568750	2	-	-	-	-	-	-	-	23	-	105	120	150	372	392	-	-	503	1178	1201	-	-
GL8A	173	405139	6566150	2	-	-	-	-	-	11	-	56	-	95	113	-	323	-	-	-	-	-	-	583	-
RAE1	217	396856	6540170	12	-	-	-	-	-	-	-	53	-	66	72	83	137	-	-	-	-	-	-	-	-
VBK	130	398139	6537149	4	-	-	-	-	-	-	-	2	-	14	-	86	156	261	-	-	-	-	-	-	-
CHER1	105	396819	6533529	1	-	-	-	-	-	-	-	-	-	-	-	-	135	-	-	-	-	-	-	-	-
GG75	115	396339	6532249	-	-	-	-	-	-	-	-	-	-	-	-	110	171	-	-	-	275	-	-	-	-
GG85	100	396539	6531749	-	-	-	-	-	-	-	-	-	-	-	-	79	-	-	-	-	-	-	-	-	-
MBRK	105	399706	6532768	5	-	-	-	-	-	12	20	34	-	47	-	134	-	-	-	-	-	-	-	-	-
MCK1	127	401021	6531105	5	-	-	-	-	-	14	23	43	-	96	-	180	270	-	-	-	-	-	-	-	-
MART2	170	400739	6530349	2	-	-	-	-	-	39	45	52	-	129	-	188	-	-	-	-	-	-	-	-	-
DELE	155	398539	6529149	2	-	-	-	-	-	7	9	19	-	62	-	138	254	-	-	-	-	-	-	-	-

Table 1 (continued)

Bore ID	Ground level (m AHD)	Easting	Northing	Base of formation below ground level (m)																					
						Tk							Kco			Kwl					Kp				
				TQ	Tr	Tkm		Tkc	Kcl	Kcp	Kcg	Kcm	Kcom	Kcok	Kcoh	Kwlp	Kwlw	Kwlm	Kws	Kwg	Kpc	Kps	Kpo	Jy	Jc
GASB	115	398539	6528649	-	-	-	-	-	-	-	-	6	-	21	-	108	189	-	-	-	-	-	-	-	-
AVON	120	398039	6527349	-	-	-	-	-	-	-	-	-	-	-	-	99	231	-	-	-	-	-	-	-	-
PB3	91	399819	6527569	-	-	-	-	-	-	-	-	-	-	38	-	73	171	-	-	-	-	-	-	-	-
POL2	100	400639	6527649	4	-	-	-	-	-	9	14	30	-	75	-	195	267	-	-	-	-	-	-	-	-
PB5A	135	400539	6528049	-	-	-	-	-	-	7	11	30	-	103	-	22	317	-	-	-	-	-	-	-	-
TTD	95	400789	6527699	4	-	-	-	-	-	12	18	28	-	75	-	122	180	-	-	-	-	-	-	-	-
PRI1	208	404259	6537999	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
PER	185	407026	6533780	-	-	-	-	-	-	21	26	56	110	152	-	157	-	-	-	-	-	-	-	-	-
CUL1	179	406858	6538132	3	-	-	-	-	-	18	-	39	98	148	160	313	-	-	-	-	-	-	-	-	-
CCC	165	407789	6526599	3	-	-	-	-	-	-	-	56	116	134	165	244	-	-	-	-	-	-	-	-	-
FLO	152	405153	6511488	4	-	-	-	-	-	78	82	101	-	215	243	259	-	-	-	-	-	-	-	-	-
FEW	57	404639	6508149	18	-	-	-	-	-	-	-	-	-	124	142	154	-	-	-	-	-	-	-	-	-
RG1	145	395158	6560719	4	-	-	-	-	-	-	-	29	-	79	96	150	430	450	-	-	474	-	-	-	-
RG2	162	402362	6544403	6	-	-	-	-	-	25	34	63	-	148	196	253	450	472	-	-	485	-	-	-	-
RG3	101	403069	6520788	2	-	-	-	-	-	8	15	47	96	175	187	201	-	-	-	-	-	-	-	-	-
ML1	214	397221	6612747	-	-	-	-	-	-	13	47	83	-	208	220	282	633	645	-	-	750	-	-	-	-
ML2	206	387569	6613192	3	-	-	-	-	-	-	-	-	-	15	24	27	298	346	-	-	762	-	-	-	-
ML3	193	379207	6611513	-	-	-	-	-	-	-	-	-	-	-	-	-	12	195	-	-	482	688	717	745	-
ML4	285	368927	6610325	12	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	332	420	483	732	-
ML5	205	360391	6610238	3	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	754	-
ML6	116	352802	6608159	12	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	772	-
ML7	70	344334	6606878	42	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	800	-
ML8	39	329743	6617059	24	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
SN4134	75	372139	6569150	57	-	-	-	-	-	-	-	-	-	-	-	-	78	114	183	246	-	-	-	-	-
G7	12	386820	6473223	37	-	-	-	-	-	-	-	67	96	106	135	147	294	317	402	430	-	-	-	745	-
G17	28	383598	6474795	56	-	-	170	-	-	-	-	-	-	-	-	175	238	243	327	380	-	-	-	945	-
G27	5	383561	6469361	31	-	-	100	-	-	-	-	-	-	-	-	-	205	210	300	415	-	-	-	750	-
CL1	28	405760	6447370	20	-	-	-	-	-	-	-	-	-	-	-	-	108	230	-	290	-	-	-	600	-
CL2	23	401935	6445020	30	-	-	-	-	-	-	-	-	-	-	-	-	-	323	-	355	-	-	-	709	-

Table 1 (continued)

Bore ID	Ground level (m AHD)	Easting	Northing	Base of formation below ground level (m)																					
						Tk							Kco			Kwl					Kp				
				TQ	Tr	Tkm		Tkc	Kcl	Kcp	Kcg	Kcm	Kcom	Kcok	Kcoh	Kwlp	Kwlw	Kwlm	Kws	Kwg	Kpc	Kps	Kpo	Jy	Jc
GY1	82	392430	6534424	30	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	552	-	-	762	-
Petroleum wells (offshore)																									
QR1	-	358814	6483245	355	-	-	-	-	-	-	-	-	-	-	-	-	611	-	760	775	1590	-	1670	2210	-
C1	-	350955	6481412	410	-	-	-	-	-	-	-	-	-	-	-	-	870	-	1485	1590	2435	-	-	-	-
Mu1	-	354019	6471822	442	-	-	-	-	-	-	-	-	-	-	-	-	867	-	1505	1625	2000	-	-	-	-
GR1	-	345085	6461183	620	-	-	-	-	-	-	-	-	-	-	-	-	1048	-	1588	1803	-	-	2618	3003	-
GR2	-	343418	6462578	575	-	-	-	-	-	-	-	-	-	-	-	-	1085	-	1350	1365	1790	2850	2930	2985	-
Wa1	-	342363	6430854	1080	-	-	-	-	-	-	-	-	-	-	-	-	1490	-	1945	2070	2930	-	2965	3300	-
Pe1	-	352893	6427632	865	-	-	-	-	-	-	-	-	-	-	-	-	1280	-	1620	1730	3060	3500	3550	4000	-

Notes:

Geological units

TQ	*Superficial formations*
Tr	*Rockingham Sand*
Tk	*Kings Park Formation*
Tkm	*Mullaloo Sandstone Member*
Tkc	*Como Sandstone Member*
Kcl	*Lancelin Formation*
Kcp	*Poison Hill Greensand*
Kcg	*Gingin Chalk*
Kcm	*Molecap Greensand*
Kco	*Osborne Formation*
Kcom	*Mirrabooka Member*
Kcok	*Kardinya Shale Member*
Kcoh	*Henley Sandstone Member*
Kwl	*Leederville Formation*
Kwlp	*Pinjar Member*
Kwlw	*Wanneroo Member*
Kwlm	*Mariginiup Member*
Kws	*South Perth Shale*
Kwg	*Gage Formation*
Kp	*Parmelia Formation*
Kpc	*Carnac Member*
Kps	*Parmelia Sand*
Kpo	*Otorowiri Member*
Jy	*Yarragadee Formation*
Jc	*Cattamarra Coal Measures*

Bore names

WP	*Woodman Point*
GB	*Gingin Brook*
ML	*Moora Line*
GL	*Gillingarra Line*
GASB	*Gingin Ashby*
G7,G17&G27	*Yarragadee Drought Contingency*
P	*Pinjar*
W	*Wanneroo*
M	*Mirrabooka*
BP	*Bold Park*
YSC	*Yanchep Sailing Club*
Y	*Mt Yokine*
J	*Jandakot*
JWS	*Jandakot Water Supply*
CL	*Champion Lake*
RG	*Red Gully (WRC)*
GY1	*Gingin Yarragadee 1 (URS)*

Table 2 Stratigraphic sequence and estimated hydraulic properties of geological units in the Perth Region

Age	Stratigraphy	Symbol	Maximum thickness (m)	Lithology	Aquifer and model layer	Horizontal hydraulic conductivity (m/day)
Quaternary–Late Tertiary	Superficial formations	TQ	110	Sand, silt, clay, limestone	**Model layers 1 and 2**	5–50 sands 100–1000 limestone
	Safety Bay Sand	Qs	24	Sand and shell fragments	Superficial aquifer	15
	Becher Sand	Qc	20	Sand, silt, clay and shell fragments	Superficial aquifer	8
	Tamala Limestone	Qt	110	Limestone		100–1000
	Bassendean Sand	Qd	80	Sand and subordinate silt and clay	Superficial aquifer	15
	Gnangara Sand	Qn	30	Sand, gravel and subordinate silt and clay	Superficial aquifer	20
	Guildford Clay	Qg	35	Clay with subordinate sand and gravel	Local confining bed	0.1–1
	Yoganup Formation	Ty	10	Sand, silt, clay and pebbles	Superficial aquifer	10
	Ascot Formation	Ta	25	Limestone, sand, shells and clay		8
	Rockingham Sand	Tr	110	Sand, silt and subordinate clay	Rockingham aquifer	20
Early Tertiary	Kings Park Formation	Tk	530	Shale, calcareous and glauconitic siltstone, minor sand	Confining bed	0.1
	Mullaloo Sandstone Member	Tkm	200	Sand, clayey and glauconitic	Minor aquifers	10–15
	Como Sandstone Member	Tkc	57	Sand, minor clay		10 – 15

Table 2 (continued)

Age	**Stratigraphy**	**Symbol**	**Maximum thickness** (m)	**Lithology**	**Aquifer and model layer**	**Horizontal hydraulic conductivity** (m/day)
Cretaceous			180		**Layer 3**	4–15
	Lancelin Formation	Kcl	120	Mudstone (marl), silty, clayey and glauconitic	Local confining bed	0.1
	Poison Hill Greensand	Kcp	90	Sand, silty, clayey and glauconitic	Mirrabooka aquifer	10
	Gingin Chalk	Kcg	40	Chalk, sandy and glauconitic	Local confining bed	0.001–0.1
	Molecap Greensand	Kcm	80	Sand, clayey and glauconitic	Mirrabooka aquifer	10
	Osborne Formation	Kco	180	Sandstone, siltstone and shale		
	Mirrabooka Member	Kcom	160	Sandstone, siltstone and shale	Mirrabooka aquifer	4–5
	Kardinya Shale Member	Kcok	140	Shale, siltstone, minor sandstone	Confining bed, **Layer 4**	10^{-4}–10^{-6}
	Henley Sandstone Member	Kcoh	80	Sand, silty, clayey and glauconitic	Leederville aquifer **Layer 5**	2–3
	Leederville Formation	Kwl	600	Sandstone, siltstone and shale	Leederville aquifer	
	Pinjar Member	Kwlp	150	Sandstone, siltstone and shale	Leederville aquifer **Layer 5**	1
	Wanneroo Member	Kwlw	450	Sandstone, siltstone and shale	Leederville aquifer **Layer 6**	1 – 10
	Mariginiup Member	Kwlm	250	Sandstone, siltstone and shale	Leederville aquifer **Layer 7**	0.1 – 1
	South Perth Shale	Kws	300	Shale, siltstone, minor sandstone	Confining bed **Layer 8**	10–4 – 10–6
	Gage Formation	Kwg	350	Sandstone, siltstone and shale	Yarragadee aquifer	2 – 10

Table 2 (continued)

Age	Stratigraphy	Symbol	Maximum thickness (m)	Lithology	Aquifer and model layer	Horizontal hydraulic conductivity (m/day)
Cretaceous–Jurassic	Parmelia Formation	Kp	> 287	Sandstone, siltstone and shale		
	Carnac Member	Kpc		Shale and siltstone	Confining bed **Layer 8**	10^{-6}
	Parmelia Sand Member	Kps		Sandstone, siltstone	Parmelia Sand aquifer **Layer 9**	0.5–2
	Otorowiri Member	Kpo		Shale and siltstone	Confining bed **Layer 10**	10^{-6}
Jurassic	Yarragadee Formation	Jy	> 2 000	Sandstone, siltstone and shale	Yarragadee aquifer **Layers 11and 12**	1–3
	Cattamarra Coal Measures or Cadda Formation	Jc	> 500	Sandstone, siltstone and shale	Yarragadee aquifer **Layer 12**	1–3

Table 3 Superficial aquifer average annual net rainfall recharge

	Area (km^2)	**Net recharge (low)**		**Net recharge (high)**	
		Average recharge rate (%)	**Volume** (GL/yr)	**Average recharge rate** (%)	**Volume** (GL/yr)
PRAMS Total	7131	11	480	15	760
Perth Region	4135	13	320	18	460
Perth north	1908	16	200	20	270
Perth south	2226	11	120	16	190
Gingin	2996	6	160	10	300

Note:

The calculation is based on the long term average rainfall of 860 mm/yr at Perth Region Station. Recharge rates are linear averages.

Table 4 Streamflow and baseflow of main rivers and brooks in Perth

Station name	**Station number**	**Streamflow** (GL/year)	**Baseflow** (GL/year)	**Period**	**Baseflow/ streamflow** Ratio
Canning River downstream of Canning Dam	616027	14.9	8.1	1980–2000	0.55
Dirk Brook	614028	12.2	6.6	1980–2000	0.54
Ellen Brook	616189	30.9	17.2	1980–2000	0.56
Gingin Brook – Bookine Bookine	617003	39.8	27.7	1980–2000	0.69
Gingin Brook – Gingin	617058	12.6	10.0	1980–2000	0.80
Jane Brook	616178	10.5	5.3	1980–2000	0.50
Lennard Brook	617165	6.9	5.5	1980–2000	0.79
Moore River – Quinns Ford	617001	84.8	35.1	1980–2000	0.41
Serpentine Drain	614030	81.1	30.9	1980–2000	0.38
Southern River	616092	15.0	7.5	1998–2000	0.50
Wooroloo Brook	616001	49.9	27.7	1980–2000	0.56
Avon River – Walyunga Upper Swan	616011	377.7	240.0	1980–2000	0.63

Table 5 Summary of groundwater abstraction data estimated by various studies in the Perth Region (GL/yr)

Use Category		**1980**	**1985**	**1992**	**2001**	**2002**	**2003**	**2004**
Bore type	Use type	Allen (1981)	Cargeeg et al. (1987)	Davidson (1995)	this study	this study	this study	this study
Licensed private bore	Self supply	113	108	127	196	206	210	217
Water Corporation bore	Scheme supply	58	62	81	134	154	158	158
Unlicensed garden bore	Home garden use	60	78	77	104	107	109	112
Total		231	248	285	434	467	477	487

Note:

1980 data are from Allen (1981), Groundwater Resource of the Swan Coastal Plain Near Perth, Western Australia.

1985 data are from Cargeeg, et al. (1987), Perth Urban Water Balance Study.

1992 data are from Davidson (1995), Hydrogeology and Groundwater Resources of the Perth Region, Western Australia. Usage/allocation ratio = 0.8

2001–2004 data are from the current study. Usage/allocation ratio = 0.92.

Water Corporation data are based on fiscal year while the licensed private use data are based on calendar year

Table 6 Perth Region 2004 groundwater use

Main water use	Category	Aquifer	Uses (GL/yr)	Allocation (GL/yr)	% Category	% Main use
Licensed private use	Horticulture and agriculture use	Superficial	90	97.4		
		Mirrabooka	2	1.7		
		Leederville	8	1.6		
		Yarragadee	1	1.6		
		Total	*101*	*109.5*	46%	
	Industry and services use	Superficial	31	34.1		
		Mirrabooka	0	0.0		
		Leederville	4	4.4		
		Yarragadee	7	7.2		
		Total	*42*	*45.7*	19%	
	Park and recreation use	Superficial	38	41.1		
		Mirrabooka	0	0.2		
		Leederville	4	4.0		
		Yarragadee	0	0.3		
		Total	*42*	*45.6*	19%	
	Domestic and rural lifestyle and other use	Superficial	26	28.5		
		Mirrabooka	0	0.1		
		Leederville	3	3.6		
		Yarragadee	3	3.1		
		Total	*32*	*35.3*	16%	
		Subtotal	217	236.1		45%
Water Corporation scheme supply		Superficial	63			
		Mirrabooka	5			
		Leederville	42			
		Yarragadee	48			
		Subtotal	158			32%
Home garden use		Superficial	112			23%
		Total	487			

Aquifer	Licensed private use		Water Corporation		Unlicensed home garden use		Total	
	Use (GL/yr)	%	Use (GL/yr)	%	Use (GL/yr)	%	Use (GL/yr)	%
Superficial	185	85	63	40	112	100	360	74
Mirrabooka	2	1	5	3			6	1
Leederville	19	9	42	27			61	13
Yarragadee	11	5	48	30			60	12
Total	217		112		487			

Table 7 Perth north (Gnangara Mound) 2004 groundwater use

Main water use	Category	Aquifer	Uses (GL/yr)	Allocation (GL/yr)	% Category	% Main use
Licensed private use	Horticulture and agriculture use	Superficial	54	58.1		
		Mirrabooka	1	1.7		
		Leederville	5	5.6		
		Yarragadee	1	0.6		
		Total	*61*	*66.0*	48%	
	Industry and services use	Superficial	13	14.0		
		Mirrabooka	0	0.0		
		Leederville	2	2.3		
		Yarragadee	0	0.0		
		Total	*15*	*16.3*	12%	
	Park and recreation use	Superficial	31	33.7		
		Mirrabooka	0	0.2		
		Leederville	4	3.7		
		Yarragadee	0	0.2		
		Total	*35*	*37.8*	27%	
	Domestic and rural lifestyle and other use	Superficial	14	14.8		
		Mirrabooka	0	0.1		
		Leederville	2	2.7		
		Yarragadee	0	0.0		
		Total	*16*	*17.6*	13%	
		Subtotal	127	137.7		38%
Water Corporation scheme supply		Superficial	58			
		Mirrabooka	5			
		Leederville	40			
		Yarragadee	48			
		Subtotal	151			45%
Home garden use		Superficial	58			17%
		Total	336			

Aquifer	Licensed private use		Water Corporation		Unlicensed home garden use		Total	
	Use (GL/yr)	%	Use (GL/yr)	%	Use (GL/yr)	%	Use (GL/yr)	%
Superficial	112	88	58	39	58	100	228	67
Mirrabooka	1	1	5	3			6	2
Leederville	13	10	40	26			53	16
Yarragadee	1	1	48	32			49	15
Total	127		151				336	

Table 8 Perth south (including Jandakot Mound) 2004 groundwater use

Main water use	Category	Aquifer	Uses (GL/yr)	Allocation (GL/yr)	% Category	% Main use
Licensed private use	Horticulture and agriculture use	Superficial	36	39.3		
		Leederville	3	3.2		
		Yarragadee	1	1.0		
		Total	*40*	*43.5*	44%	
	Industry and services use	Superficial	18	20.1		
		Leederville	2	2.1		
		Yarragadee	7	7.2		
		Total	*27*	*29.4*	30%	
	Park and recreation use	Superficial	7	7.4		
		Leederville	0	0.3		
		Yarragadee	0	0.1		
		Total	*7*	*7.8*	8%	
	Domestic and rural lifestyle and other use	Superficial	12	13.7		
		Leederville	1	0.9		
		Yarragadee	3	3.1		
		Total	*16*	*17.6*	18%	
		Subtotal	90	98.3		60%
Water Corporation scheme supply		Superficial	5			
		Leederville	2			
		Yarragadee	–			
		Subtotal	7			5%
Home garden use		Superficial	54			35%
		Total	151			

Aquifer	Licensed private use		Water Corporation		Unlicensed home garden use		Total	
	Use (GL/yr)	%	Use (GL/yr)	%	Use (GL/yr)	%	Use (GL/yr)	%
Superficial	73	81	5	70	54	100	132	88
Leederville	6	7	2	30	0		8	5
Yarragadee	11	11	0	0	0		11	7
Total	90		7		54		151	

Glossary

abstraction	pumping groundwater from an aquifer
Australian height datum	Mean sea level (MSL) + 0.026 m; Low water mark Fremantle (LWMF) + 0.756 m
alluvium (alluvial)	detrital material which is transported by streams and rivers and deposited
Australian map grid	standard six-figure reference system whereby the first group of figures (easting) and the second group (northing) together uniquely define the position surveyed to within one metre
anisotropy	the degree of variation of hydraulic conductivity between the vertical and horizontal directions at a point in an aquifer
anticline	sediments folded in an arch
aquifer	a geological formation or group of formations able to receive, store and transmit significant quantities of water
unconfined aquifer	a permeable bed only partly filled with water and overlying a relatively impermeable layer. Its upper boundary is formed by a free watertable or phreatic level under atmospheric pressure
confined aquifer	a permeable bed saturated with water and lying between an upper and a lower impermeable layer
semi-confined	a semi-confined or leaky aquifer is saturated and bounded above by a semi-permeable layer and below by a layer that is either impermeable or semi-permeable
semi-unconfined	intermediate between semi-confined and unconfined, when the upper semi-permeable layer easily transmits water
artesian aquifer (bore)	a confined aquifer with sufficient hydraulic head that the water in a bore would rise above the ground surface
perched aquifer	an unconfined aquifer separated from an underlying body of groundwater by an unsaturated zone (contains a perched watertable)
artesian basin	a series of sedimentary beds disposed in such a way that an aquifer holds water under a pressure head between two less permeable beds.
base flow	that portion of river and streamflow coming from groundwater discharge
basin (geological)	a depression of large size, which may be of structural or erosional origin (contains sediments)

beds (geological)	a subdivision of a formation: smaller than a member
biota	all plants and animals within a specified area
bioturbated	sediments stirred by organisms
bore	small-diameter well, usually drilled with machinery
coffee rock	colloquial term for iron oxide (limonite)-cemented sand grains
colloid	suspended microscopic particles in water
colluvium (colluvial)	material transported by gravity down hill slopes
confining bed	sedimentary bed of very low hydraulic conductivity
conformably	sediments deposited in a continuous sequence without a break
unconformably	time break in sequence of deposition
Cretaceous	final period of the Mesozoic era spanning 65–135 million years ago
delta (deltaic)	sediments deposited at the mouth of a river where it enters a lake or the ocean
density	the mass of water per unit volume, usually stated in g/cm^3
discharge (groundwater)	all water leaving the saturated part of an aquifer
doline	synonym for sinkhole (karst feature)
effective porosity	drainable pore space, considered synonymous with specific yield of unconfined aquifer
eolian	wind-blown; deposit formed by wind action
ephemeral stream	stream or river that flows briefly in direct response to rainfall and whose channel is above the watertable
estuary (estuarine)	the seaward or tidal mouth of a river where fresh water comes into contact with seawater
eustatic	pertaining to worldwide changes of sea level that affect all the oceans
evapotranspiration	a collective term for evaporation and transpiration
facies	a mappable lithostratigraphic unit, differing in lithology from adjacent units deposited at the same time and in lithological continuity
fault	a fracture in rocks or sediments along which there has been an observable displacement
field capacity	soil moisture retained by capillarity, not removable by gravity drainage
fluvial	pertaining to streams and rivers

flux	outflow
formation (geological)	a group of rocks or sediments which have certain characteristics in common and which were deposited about the same geological period and constitute a convenient unit for description
Geographical information systems	An arrangement of computer hardware, software and geographic data that people interact with to integrate, analyse and visualise the data; identify relationships, patterns and trends; and find solutions to problems. Such a system is designed to capture, store, update, manipulate, analyse and display the geographic information. A GIS is typically used to represent maps as data layers that can be studied and used to perform analyses.
Groundwater modelling system	modelling software developed by the U.S. Defence Department (EMS-I, 2002)
Gondwana	The Late Palaeozoic continent of the Southern Hemisphere
graben	a downthrown elongate block that is bounded by faults on its long sides
group (geological)	includes two or more contiguous or associated formations with significant lithological features in common
hydraulic	pertaining to groundwater motion
conductivity (permeability)	ease with which water is conducted through an aquifer
gradient	the rate of change of total head per unit of distance of flow at a given point and in a given direction
head	the height of the free surface of a body of water above a given subsurface point
hypersaline	excessively saline; with a salinity substantially greater than that of sea water
infiltration	movement of water from the land surface to below ground level
interfinger	lithological facies being conformably and alternatingly deposited
isopach	a contour line joining points of equal geological-unit thickness
isopotential	equipotential; having uniform hydraulic head
Jurassic	the second period of the Mesozoic era spanning 135–190 million years ago
juxtaposition	side by side

karst	a type of topography that is formed on limestone by dissolution, and that is characterised by sink holes, caves, dolines, solution channels and underground drainage
lacustrine	pertaining to, produced by, or formed in a lake
lateritised (lateritic)	a surficially formed deposit consisting mostly or entirely of iron and/or aluminium oxides and hydroxides
leach (leaching)	removal of soluble matter by percolation of water
leakage (groundwater)	movement of groundwater from one aquifer to another
levee	bank of a watercourse
member (geological)	a lithostratigraphic unit of subordinate rank, comprising some specially developed part of a formation
Mesozoic	an era of geological time spanning 65–225 million years ago
model (modelling system)	a simplified version of the groundwater system that approximately simulates the excitation-response relations of the real system
neritic	pertaining to the ocean environment or depth zone between low-tide level and the edge of the continental shelf
Neocomian	lowermost stage of the Cretaceous period
oxidising	combine with oxygen
palaeolake	ancient lake
palynology	study of pollen of seed plants and spores of other embryophytic plants, whether living or fossil, including their dispersal and applications in stratigraphy and palaeoecology
paralic	pertaining to interfingered marine and continental deposits laid down on the landward side of the coast or in shallow water (lagoonal or littoral) subject to marine invasion
percolation	movement of water from the land surface to the watertable after infiltration
penecontemporaneous	almost at the same time
permeable	ability to permit water movement
pH	the negative decimal logarithm of hydrogen ion concentration. For example, pure water at 25°C contains 10^{-7} g/L of H+ ion; its pH is 7.00
piedmont	a plain or foothill at the base of a mountain or high range
plain	tract of flat or level terrain

plateau	an extensive land region considerably elevated (more than 150 m in altitude) above the adjacent country or above sea level
pore space	the open spaces in sediments, considered collectively
potentiometric surface	an imaginary surface representing the total head of groundwater and defined by the level to which water will rise in a bore. The watertable is a particular potentiometric surface
PRAMS	Perth Region Aquifer Modelling System
puggy	plasticine-like consistency
Quaternary	the latest period in the Cainozoic era
recharge (groundwater)	all water reaching the saturated part of an aquifer (artificial or natural)
reducing	remove oxygen or undergo addition of electrons
salinity	a measure of the concentration of total dissolved solids (TDS) in water 0–500 mg/L, fresh 500–1500 mg/L, fresh to marginal 1500–3000 mg/L, brackish 3000 mg/L and greater, saline
scarp	a line of cliffs (steep slopes) produced by faulting or by erosion
shelf	shallow, marginal part of a sedimentary basin
solution channel	tubular or planar channel formed by solution of calcium carbonate in limestone
specific yield	the volume of water that an unconfined aquifer releases from storage per unit surface area of the aquifer per unit decline in the watertable
storage coefficient	the volume of water that a confined aquifer releases from storage per unit surface area of aquifer per unit decline in the component of hydraulic head normal to that surface
stratigraphy	the science of rock strata. Concerned with original succession and age relations of rock strata and their form, distribution, lithology, fossil content, geophysical and geochemical properties
surfactant	substance which reduces surface tension
sustainable (yield)	level of groundwater extraction measured over a specified planning timeframe that should not be exceeded to protect the higher value social, environmental and economic uses associated with the aquifer

swale	a slight depression, sometimes swampy, in generally level land
syncline	a basin shaped fold in sedimentary strata
tectonic	pertaining to the forces involved in major earth movements in, or the resulting structures or features of, rocks
Tertiary	the first period of the Cainozoic era spanning two to 65 million years ago
throughflow (groundwater)	groundwater flow within an aquifer
transmissivity	the rate at which water is transmitted through a unit width of an aquifer under a unit hydraulic gradient
transpiration	the loss of water vapour from a plant, mainly through the leaves
trough (geological)	a linear depression or basin that subsides as it receives clastic material, located not far from the source supplying the sediment
type (locality, section)	the place at which a stratotype is situated and from which it derives its name
watertable	the surface of a body of unconfined groundwater at which the pressure is equal to that of the atmosphere
well	large-diameter bore, usually dug or drilled for abstracting groundwater; also petroleum bore
yield	sustainable rate at which a bore or well can be pumped

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