Government of **Western Australia**
Department of **Water**

Conceptual geology of the North Gnangara Mound

JP Pigois

Groundwater Investigation Section

Looking after all our water needs

Milestone 4.1c Gnangara

Department of Water

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Water for the Future

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Summary

Over the past thirty years, there has been increasing utilisation of the unconfined and confined aquifers beneath Perth for water supply. This ongoing dependence on groundwater resources to meet water demand requires an improved understanding of the Perth's groundwater resources.

The Department of Water and Water Corporation have been working, in collaboration, on a groundwater resource investigation in the northern portion of the Gnangara Mound. The North Gnangara groundwater investigation was also part funded by the Australian Government under Water for the Future's – Water Smart Australia program.

The investigation was a high priority due to poor calibration of the Perth Regional Aquifer Modelling System (PRAMS) in this area, and the need to resolve hydraulic connection between aquifers. Traditional investigations comprising monitoring bore installation and data interpretation on cross-sections was considered not sufficient and two-dimensional to significantly improve the conceptual geological understanding in PRAMS. As a result, a new and innovative methodology was developed focusing on improving the three-dimensional (3D), conceptual understanding of aquifer distribution across the northern Gnangara Mound.

As part of the investigation, 65 monitoring bores were installed into the superficial, Leederville and Yarragadee aquifers. Of these, 49 have permanent water level loggers installed to record six-hourly levels. The new monitoring bores and increased measurement frequency will assist in resolving declining water levels and provide more comprehensive monitoring across the northern Gnangara Mound.

In order to improve the conceptual model, a shift from collecting 2-D to 3-D information required the integration of innovative techniques. More than 50 km of seismic transects were collected by Curtin University to further improve the spatial understanding of stratigraphy. This new research has successfully collected high resolution, geophysical data from the surface to 1000 m below ground level.

Petrel, a petroleum industry software package, was selected to incorporate all data collected for easily importing, interrogation and interpretation from a 3-D perspective. This spatial presentation of data is unparalleled when compared with previous investigations. Geological interpretations were considerably simpler to make and are considered more robust. As a result, it has been possible to generate a full 3-D appreciation of the stratigraphy in the northern Gnangara Mound.

An important objective was achieved with the hydraulic window into the Yarragadee aquifer being delineated. Other major findings were that there is no folding of the stratigraphy; faulting is a more important structural control and the Parmelia Formation separates the Leederville Formation into two distinct entities. These stratigraphic findings are crucial to creating a more accurate and robust conceptual

hydrogeological model for the numerical PRAMS model. Ultimately, this will lead an improved PRAMS model resulting in better groundwater resource management and decision making.

1 Introduction

1.1 Background

In recent years, the northern portion of the Gnangara Mound has been experiencing declining water levels. The investigation area (referred to as North Gnangara) has experienced increasing local groundwater demand and pressures from horticultural development. The additional impact of a drying climate has required an increased understanding of the constraints / limitations on groundwater resources, so that the Department of Water can make informed decisions on aquifer sustainability and acceptable impacts.

In addition to local impacts, there has been 20 years of abstraction from the Yarragadee aquifer for Perth's water supply resulting in regional aquifer depressurisation. This is significant for the northern Gnangara Mound with Davidson and Yu (2005) suggesting hydraulic connection and active, modern recharge into the Yarragadee aquifer related to an interpreted hydraulic window. The confirmation of position and extent of this recharge window is critical for management of confined aquifers into the future.

Furthermore, Davidson and Yu (2008) highlighted difficulties in attaining good calibration of water levels within PRAMS (Perth Regional Aquifer Modelling System) groundwater model, particularly in the northern Gnangara Mound. The new data will improve the conceptual geological model and subsequently improve reliability and confidence in PRAMS predictions.

The North Gnangara groundwater investigation, part of the Department of Water's State Groundwater Investigation Program (SGIP), is managed by the Groundwater Investigation Section. The SGIP focuses on investigating and monitoring areas of increased groundwater usage, and where current groundwater knowledge is insufficient to allow groundwater resource assessment and appropriate groundwater management.

Funding of the investigation was through SGIP and the Australian Government's Water for the Future's – WaterSmart Australia program. The total cost of the project was approximately $3.3 million, of which Water Smart Australia contributed $1.2 million. The WaterSmart Australia contribution was used for constructing access tracks, drilling pads and installing surface casing. The remaining $2.1 million was allocated from the SGIP capital budget for bore installation.

1.2 Purpose and scope

The North Gnangara investigation aims to establish a new groundwater monitoring network in the northern Gnangara Mound, which will infill and address a significant knowledge gap identified by Davidson and Yu (2005). The new bores are to be integrated into the State's groundwater monitoring network.

The investigation will improve understanding of the stratigraphy, aquifer distribution and hydraulic connection between the Superficial, Leederville and Yarragadee aquifers. All drilling and geophysical data will be integrated to develop a 3-D conceptual geological model for the northern Gnangara Mound. Improvements related to this conceptual model are to be incorporated into the next version of PRAMS model to improve model calibration and reliability.

The deliverables of the investigation include:

- Installing new groundwater monitoring bores at selected intervals within the superficial, Leederville and Yarragadee aquifers
- Electronic capture of all data collected into WIN database (including lithological, geophysical, chemical and bore construction data)
- A bore completion report for each new monitoring bore (hard copy plus electronic capture)
- Improved conceptual geological and hydrogeological understanding / model using Petrel and incorporating findings into PRAMS
- A hydrogeological report (HG) on the drilling results and improved spatial understanding of the investigation area

This document discusses the installation of monitoring bores, and integration of data collected from a shallow geophysical survey, which has led to the development of a 3-D conceptual geological model. There is very little discussion about hydrogeology and groundwater resources management, as there are still substantial works being the focus of existing work.

1.3 Location

The investigation area is located at the northern part of the Gnangara Mound being 70 km north of Perth and 20 km west of Gingin (Figure 1). It is bounded to the north by Gingin Brook, the east by Brand Highway, the west by Military and Water Roads, and the south by Airforce Road. This covers an area of more than 1400 square kilometres.

There are six bore sites (NG1, 3, 4, 8, 9 and 10) located on Department of Environment and Conservation (DEC)-managed land, namely within the Yeal Nature Reserve. Three bore sites (NG2, 13 and 14) are positioned within road reserves that are managed by the Shire of Gingin, while another four site (NG5, 6, 9 and 12) are positioned within private properties.

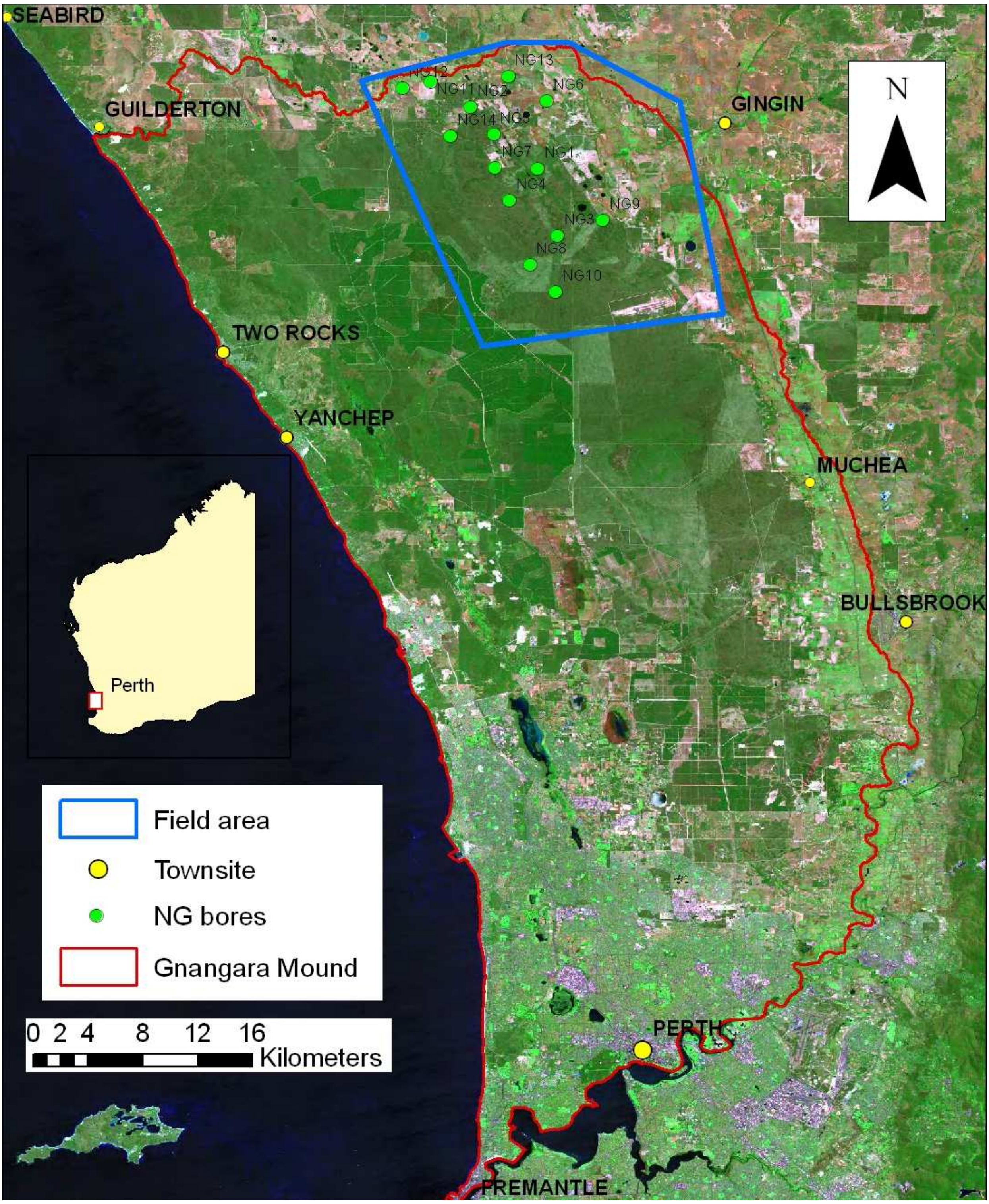

Figure 1 Location of project area.

1.4 Climate

The area has a Mediterranean climate with mild, wet winters and hot dry summers. The nearest weather station is located in the town of Gingin (Bureau of Meteorology station number 9018). Long-term average rainfall between 1889 and 2008 is 732 mm/yr, while the average rainfall for the past 40 years is lower at 658 mm/yr. Figure 2 shows that the 20 year moving average for rainfall has been declining in incremental steps since the mid-1930s. Pan evaporation is about 2200 mm/yr and rainfall only exceeds evaporation during the winter months of May to August.

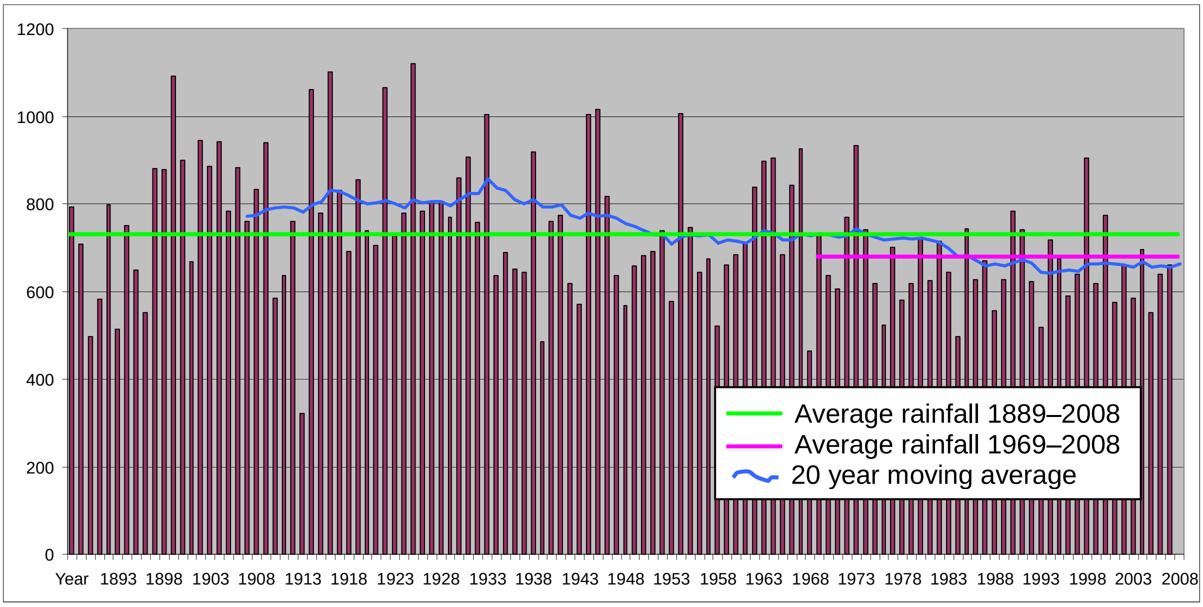

Figure 2 Measured yearly rainfall at Gingin weather station from 1889 to 2008.

1.5 Physiography

The investigation area lies entirely within the Swan Coastal Plain. It is bounded to the east by the Gingin Scarp, which rises to over 200 m AHD, and represents the eastern boundary of marine erosion during the Tertiary and Quaternary. The Pinjarra Plain, about 5 km wide, abuts the Gingin Scarp and comprises clayey alluvium eroded from the Dandaragan Plateau. The Bassendean Dune system makes up the rest of the investigation area with gently undulating eolian dunes ranging from 35 to 65 m AHD that run parallel to the coast.

Gingin Brook is the most prominent drainage and forms the northerly extent of the investigation area. It was historically perennial; however, baseflow resulting from groundwater discharge in some reaches has ceased (Tuffs, in prep). Quin Brook, a tributary of Gingin Brook, cuts across the investigation area but it only flows in response to winter rainfall.

There are many wetlands classified as lakes, sumplands and palusplains. These are found in interdunal swales and depressions, and are seasonally waterlogged. The main lakes and swamps are Yeal Lake, Muckenburra Lake and Quin Swamp, which are all EPP wetlands. Other significant wetlands include Central Yeal wetlands, and Tangletoe Swamp. Monitoring sites have been established in these wetlands, as part of a review of shallow groundwater systems on the Gnangara Mound (McHugh and Bourke, 2007).

1.6 Vegetation and land use

Throughout the investigation area, there has been widespread development for horticulture, turf, market gardens, commercial orchards, fertilised pasture for grazing, and semi-rural residential development. The extent of development is most intensive within one to two kilometres either side of the Gingin Brook. The Yeal Nature Reserve is of significant area of remnant vegetation comprising banksia woodlands, related to the Bassendean North vegetation complex type (Heddle, 1980).

2 Field investigation program

2.1 Approach

Traditional groundwater investigations comprised the installation of monitoring bores with data interpreted on cross-sections. This approach was considered inadequate to significantly improve the numerical groundwater model, which required a greater spatial, 3-D appreciation of aquifer distribution. It was necessary to develop an innovative methodology so that the resultant conceptual geological model was a meaningful and realistic representation of stratigraphy. In order to achieve this objective, a number of innovative and established techniques were applied as part of the investigation including:

- 49 monitoring bores installed by the Department of Water at 12 sites within the superficial, Leederville and Yarragadee aquifers
- Gamma and induction logs in the deepest bores for selecting screen position and determining stratigraphic continuity
- Palynological analysis to estimate geological age and stratigraphic relationships
- Data loggers with six hourly measurements for improved groundwater model calibration, resolving recharge responses, and aquifer connectivity
- High resolution, shallow seismic surveys developed by Curtin University Department of Exploration Geophysics to resolve stratigraphic continuity between bore holes, and geological structure such as dipping strata and faults
- Vertical-seismic profiling and full-wave form sonic logging to accurately calibrate the 2D seismic data (via time to depth conversion) and to acoustically characterize hydrostratigraphic units
- Ground-penetrating radar and vertical-radar profiling to assist in mapping recharge characteristics of the superficial formations (in particular, water retentive layers)

The shift from collecting and presenting geological information from 2-D to 3-D relates to the need for better spatial appreciation of the complex hydrogeology in the Perth Basin. This shift has only been possible with the introduction and application of shallow geophysical techniques, primarily high-resolution 2D seismic reflection and ground penetrating radar surveys.

The geophysical results, in combination with traditional drilling and sampling data, have been entered into Petrel software to develop a 3-D conceptual geological model being a major achievement. This document details the successful integration of all data sets and development of the conceptual geological model, which will greatly improve the accuracy and precision of PRAMS.

2.2 Site access

Site approvals were required prior to the commencement of the groundwater investigations. There was long and extensive consultation, more than two years, with the Department of Environment and Conservation (DEC), Shire of Gingin and the local indigenous groups.

In order to access bore sites within the Yeal Reserve, existing sand tracks were upgraded to permit the movement of heavy vehicles. The upgraded tracks are shown, in orange, on Figure 3. The Department of Water and Water Corporation entered into an agreement to share project management and construction costs for the limestone tracks and drill pads. WaterSmart Australia funding was used to fund the first phase of track improvements in 2007/8.

More than 16.5 km of limestone track, up to four metres wide, were constructed in late 2007 (Figure 4). Drill pads, approximately 25 x 25 m, were required at each bore site for drilling rig stability and providing adequate working areas for support equipment (Figure 5). The construction of the drilling pads and track improvement was a significant achievement in its own respect, as it was a major road construction / engineering feat.

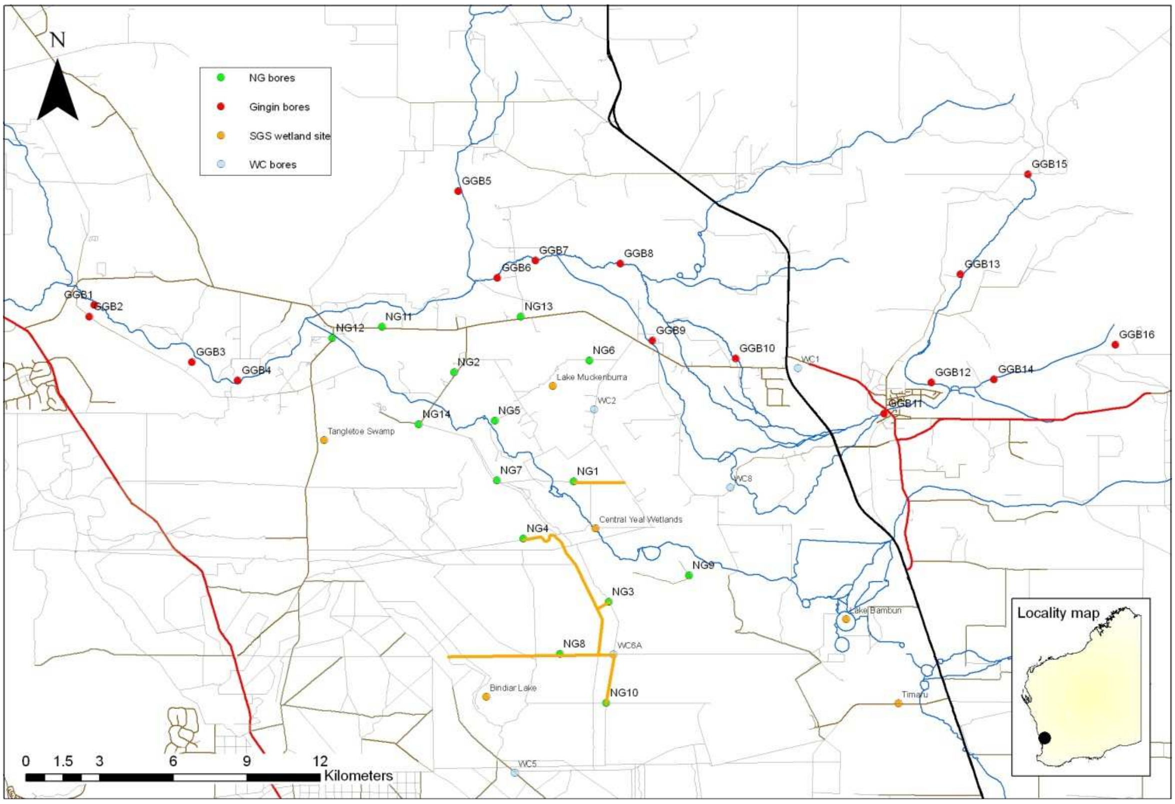

Figure 3 Location of drill sites and constructed limestone tracks (orange lines).

Figure 4 Limestone road constructed on Stewart Road.

Figure 5 Mud rotary drilling underway at site NG10.

2.3 Drilling and bore construction

The Department of Water installed a total of 49 bores at 12 sites (Figure 3), with between three and five bores at each site. Individual bores were constructed to intersect the watertable, superficial and Leederville aquifers at all sites. While, deep monitoring bores were installed at nine sites into the Yarragadee aquifer. In addition to the Department's investigation, Water Corporation installed a further 17 bores at five sites (Water Corporation, 2008). A summary from all bores is shown in Table 1.

Mud rotary drilling commenced on June 2007; however, there were drilling problems at the first two sites with significant mud loss related to the shallow karstic terrain. Fearing safety concerns to site stability and drilling personnel, it was decided that the mud rotary drilling rig was demobilised in August 2007.

As a result, surface casings for all Leederville and Yarragadee bores (Figure 6) were recommended to resolve the drilling difficulties. Two cable tool rigs between September 2007 and August 2008 installed surface casings through the superficial formations and bedded into the Leederville Formation.

Mud rotary drilling recommenced in May 2008 and finished in September 2008. Two sites, NG7 and NG11, had exploration drill holes into the Leederville aquifer but no monitoring bores were constructed. These holes were geophysically logged prior to cement grouting to prevent aquifer interconnection.

All watertable and base of the superficial aquifer bores were constructed with 50 mm Class 12 PVC and screened with in-line slotted PVC casing. Leederville bores and Yarragadee bores were typically constructed with 100 mm fibre-reinforced plastic (FRP) main casing, with a 65 mm screen assembly comprising an M-packer attached to a wire-wound, stainless steel screen and a sump to collect any fines. This construction allows the screen assembly to be removed for maintenance in the future.

All bores were developed using airlifting and jetting of the screens, until the water was clear free of fine particles and the pH, salinity and temperature had stabilised. Following development, the bores were completed with a lockable mild steel headwork secured to a concrete block flush with ground level (Figure 7).

A bore completion report (Pigois, 2009) provides a comprehensive account of location, construction, lithology and sampling for each bore. This report was previous provided to the Department of Environment, Water, Heritage and the Arts in June 2009 to met the requirement of Milestone 5.

Figure 6 Cable tool drilling rig at site NG1.

Figure 7 Completed investigation site NG13 with four monitoring bore (watertable, base of superficial, Leederville and Yarragadee)

Table 1 Bore construction summary.

Bore	Date Drilled*	Easting (MGA94)	Northing (MGA94)	Total Depth (m)	Main Casing Type	Main Casing Diameter (NB mm)	Screen Interval (m bgl)	Screen Diameter (mm)	Screened Aquifer	Natural Surface (m AHD)	Top of Concrete (m AHD)	Top of casing (m AHD)	Top of Headworks (m AHD)
NG1A	21/5/05 to 26/5/08	384945	6528302	280	FRP	100	269–275	65	Yarragadee	60.44	60.460	60.827	61.196
NG1B	26/5/08 to 27/5/08	384950	6528301	115	FRP	100	106–112	80	Leederville	60.39	60.417	60.811	61.152
NG1C	31/10/08 to 17/11/08	384955	6528301	49	PVC	50	44–47	50	Superficial	60.36	60.358	-	61.088
NG1D	19/11/08 to 25/11/08	384960	6528300	22	PVC	50	17–20	50	Superficial	60.33	60.340	-	61.068
NG2A	16/08/08 to 19/08/08	380718	6532680	118	PVC	100	104–110	80	Leederville	49.95	49.965	50.426	50.707
NG2B	4/09/08 to 10/09/08	380723	6532679	44	PVC	50	39–42	50	Superficial	49.80	49.824	50.112	50.519
NG2C	20/08/2008	380728	6532678	17	PVC	50	12–15	50	Superficial	49.61	49.649	50.271	50.373
NG3A	30/05/08 to 04/07/08	386213	6523420	232	FRP	100	223–229	65	Yarragadee	66.71	66.736	67.254	67.505
NG3B	5/07/2008	386208	6523418	143	PVC	100	135–141	80	Leederville	66.73	66.769	67.289	67.514
NG3C	6/07/2008	386203	6523417	50	PVC	50	45–48	50	Superficial	66.74	66.777	67.323	67.507
NG3D	6/07/2008	386201	6523416	16.5	PVC	50	11.5–14.5	50	Superficial	66.74	66.762	67.346	67.504
NG4A	7/07/08 to 13/07/08	383209	6525954	278	FRP	100	269–275	65	Yarragadee	59.65	59.708	60.187	60.441
NG4B	13/07/08 to 15/07/08	383210	6525949	173	FRP	100	164–170	65	Yarragadee	59.67	59.686	60.216	60.440
NG4C	15/07/08 to 16/07/08	383210	6525943	115	PVC	100	107–113	80	Leederville	59.68	59.701	60.184	60.445
NG4D	16/07/2008	383211	6525938	53	PVC	50	48–51	50	Superficial	59.71	59.724	60.431	60.469
NG4E	16/07/2008	383212	6525932	11	PVC	50	6–9	50	Superficial	59.66	59.671	60.359	60.414
NG5A	15/06/08 to 20/06/08	382172	6530732	300	FRP	100	291–297	65	Yarragadee	54.53	54.588	55.089	55.322
NG5B	26/7/08 to 3/08/08	382170	6530739	91	PVC	100	82–88	80	Leederville	54.57	54.607	55.118	55.359
NG5C	7/01/08 to 21/10/08	382167	6530743	50	PVC	50	42–48	50	Superficial	54.55	54.555	-	55.235
NG5D	23/10/08 to 30/10/08	382165	6530747	19	PVC	50	14–17	50	Superficial	54.48	54.489	-	55.176
NG6A	26/7/08 to 3/08/08	385431	6533204	299	FRP	100	290–296	65	Yarragadee	56.62	56.627	57.104	57.384
NG6B	16/5/08 to 18/05/08	385431	6533209	123	FRP	100	115–121	65	Leederville	56.60	56.625	56.953	57.375
NG6C	12/08/08 to 28/08/08	385431	6533214	43	PVC	50	35–41	50	Superficial	56.56	56.580	57.043	57.318
NG6D	02/09/08 to 08/09/08	385431	6533220	21	PVC	50	16–19	50	Superficial	56.51	56.531	56.882	57.275
NG8A	28/7/08 to 3/08/08	384536	6521309	266	FRP	100	257–263	65	Yarragadee	62.28	62.309	62.820	63.044
NG8B	3/08/08 to 5/08/08	384536	6521304	178	FRP	100	169–175	65	Yarragadee	62.31	62.327	62.895	63.079
NG8C	5/08/08 to 6/08/08	384536	6521299	116	PVC	100	108–114	80	Leederville	62.35	62.369	62.942	63.107
NG8D	6/08/2008	384536	6521295	47	PVC	50	42–45	50	Superficial	62.32	62.340	62.996	63.085

Bore	Date Drilled*	Easting (MGA94)	Northing (MGA94)	Total Depth (m)	Main Casing Type	Main Casing Diameter (NB mm)	Screen Interval (m bgl)	Screen Diameter (mm)	Screened Aquifer	Natural Surface (m AHD)	Top of Concrete (m AHD)	Top of casing (m AHD)	Top of Headworks (m AHD)
NG8E	6/08/2008	384535	6521290	17	PVC	50	12–15	50	Superficial	62.35	62.365	63.067	63.101
NG9A	23/08/08 to 27/08/08	389013	6524545	305	FRP	100	296–302	65	Yarragadee	67.67	67.690	68.234	68.451
NG9B	27/08/08 to 28/08/08	389010	6524549	150	PVC	100	142–148	80	Leederville	67.69	67.716	68.212	68.463
NG9C	28/08/2008	389008	6524553	51	PVC	50	44–47	50	Superficial	67.64	67.660	68.208	68.407
NG9D	28/08/2008	389005	6524558	23	PVC	50	18–21	50	Superficial	67.61	67.647	68.183	68.379
NG10A	19/07/08 to 26/07/08	386171	6519336	311	FRP	100	300–306	65	Yarragadee	66.47	66.476	67.019	67.211
NG10B	26/07/08 to 27/07/08	386166	6519338	95.5	PVC	100	87.5–93.5	80	Leederville	66.42	66.422	67.031	67.175
NG10C	27/07/2008	386162	6519339	56	PVC	50	51–54	50	Superficial	66.41	66.425	67.117	67.160
NG10D	27/07/2008	386158	6519340	16	PVC	50	11–14	50	Superficial	66.42	66.432	67.103	67.180
NG12A	21/08/08 to 22/08/08	376443	6534012	107	PVC	100	99–105	80	Leederville	37.39	37.469	37.441	37.485
NG12B	11/09/08 to 25/09/08	376444	6534018	38	PVC	50	31–34	50	Superficial	37.27	37.286	37.236	37.294
NG12C	25/06/07 to 26/06/07	376447	6534029	11.4	PVC	50	6.4–9.4	50	Superficial	36.67	36.740	36.389	36.744
NG13A	26/07/07 to 3/08/07	383023	6534943	179	FRP	100	167–173	65	Leederville	50.23	50.232	50.738	50.960
NG13B	4/08/2007	383027	6534943	104.5	PVC	80	95.5–101.5	80	Leederville	50.19	50.187	50.689	50.929
NG13C	5/08/2007	383029	6534943	49.5	PVC	50	40.5–46.5	50	Superficial	50.19	50.175	50.891	50.921
NG13D	6/08/2007	383032	6534944	20	PVC	50	12–18	50	Superficial	50.19	50.183	50.917	50.937
NG14A	2/06/08 to 8/06/08	379507	6530558	311	FRP	100	300–306	65	Yarragadee	52.17	52.179	52.653	52.907
NG14B	9/06/08 to 12/06/08	379509	6530562	219	FRP	100	211–217	65	Yarragadee	52.13	52.141	52.546	52.850
NG14C	12/06/08 to 13/06/08	379511	6530566	92.5	PVC	100	83.5–89.5	80	Leederville	52.08	52.109	52.471	52.831
NG14D	19/08/2008	379514	6530571	50	PVC	50	45–48	50	Superficial	52.01	52.032	52.746	52.779
NG14E	19/08/2008	379516	6530576	20	PVC	50	15–18	50	Superficial	51.98	52.000	52.694	52.740

* Date drilled does not include the dates the surface casing was installed.

- Not measured.

2.4 Sampling, logging and testing

Lithological samples were collected and logged at one metre intervals and placed into chip trays. Selected samples were submitted to Biostrat Pty Ltd for palynological analysis. Bulk samples were also retained for backup. All samples are stored at the Groundwater Investigation Depot at John Street, Welshpool.

Downhole geophysical logs were run by Westlog Pty Ltd. This included gamma ray and resistivity measurements from the open drill holes prior to bore construction.

Upon completion, airlifted groundwater samples were field tested for pH, temperature (ºC), total dissolved solids (TDS, mg/L) and electrical conductivity (EC, µS/cm) with hand-held water quality meters.

In addition, air-free groundwater samples were also collected from bores in March and April 2009 and submitted for major ion analysis. To ensure samples were representative of the screened intervals, constant field measurements were recorded with a multi-parameter probe and a flow cell for pH, temperature, EC, TDS, dissolved oxygen (DO, mg/L) and oxidation reduction potential (ORP, mV).

2.5 Levelling

Each monitoring bore was surveyed to Australian Height Datum (AHD) by GHD Surveys during November and December 2008. The top of each bore casing, headworks (cap removed), cement block and ground surface were surveyed. In addition, two control points and an additional reference mark for redundancy were installed at each site. The survey control point consists of a star iron picket at ground level with a GHD Surveys witness place located adjacent to each control point. Coordinates for each bore are presented in Table 1.

2.6 Monitoring

All bores have been fitted with non-vented data loggers (In-Situ Inc. Level TROLL100) to record pressure, water level and temperature once every six hours. One barometer (In-Situ Inc. BaroTROLL) was also installed at each bore site to record barometric pressure to compensate for water level changes related to barometric fluctuations.

All data loggers were installed in late December 2008, except for NG12A. Bore NG12A was artesian and required a different type of installation and data logger, which was installed in October 2009. Manual water level measurements were recorded monthly prior to data logger installation, as well as each time data loggers are downloaded. All water level measurements are captured digitally into the Department's HYDSTRA and WIN databases for public access with enquiries to waterinfo@water.wa.gov.au.

2.7 Shallow geophysical survey

Seismic has been successfully used for many years as a tool in petroleum exploration to map linear features including faults and stratigraphic units; however, these projects usually had deep exploration targets in excess of 1000 m. Until recently, the method was limited in near-surface exploration.

Research conducted in Western Australia by Curtin University of Technology Department of Exploration Geophysics has developed techniques to apply this method to imaging geological units and structures in the shallow, near surface. Curtin University were contracted to undertake a shallow geophysical survey across the investigation area (

Figure 8). The primary objective of the survey was to generate a high quality geophysics dataset that was suitable for resolving the detailed hydrogeology of the North Gnangara mound.

The survey, as part of a larger collaborative project between Department of Water, Water Corporation and Curtin University of Technology, involved the acquisition and processing of seismic reflection and ground penetrating radar data. Vertical seismic profiling (VSP) and full-wave form (FWF) sonic logs were also collected from NG3 to support the processing and interpretation of the seismic data.

More than 50 km of survey data was collected during mid to late 2007. There have been more than six months of processing and interpretation with the initial results being highly promising. A more thorough description of data acquisition and processing techniques is detailed in Curtin University of Technology (2009).

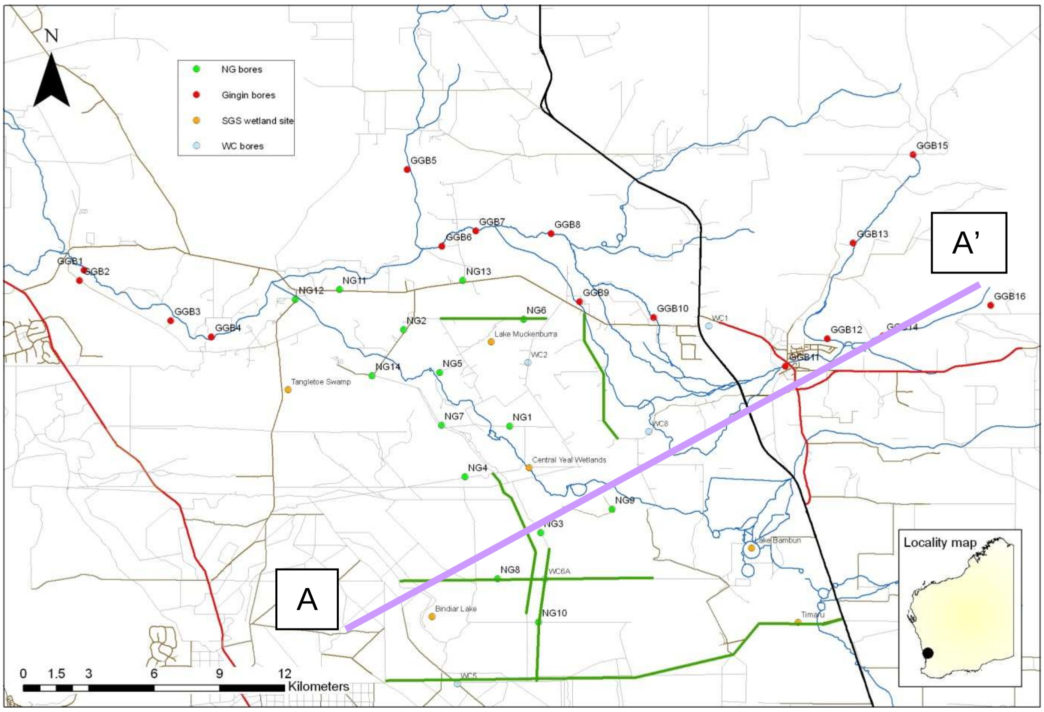

Figure 8 Geophysical transects represented by green lines and cross section by the purple line (AA').

3 Geology

3.1 Regional setting

The investigation area is located at the centre of the Perth Basin, which is made up of sediments over 10 000 m thick (Playford and others, 1976; Davidson, 1995). Sediments of Jurassic, Cretaceous and Cainozoic age were intersected during drilling with the stratigraphical sequence being outlined in Table 2.

The regional structure of the Perth Basin is dominated by north to northwest trending faults; the Badaminna Fault in the west and Gingin Fault to the east. These faults are a product of major structural events during the Neocomian related to continental break-up and seafloor spreading.

Davidson and Yu (2008) suggested that the Mesozoic sediments are gently folded to form the Yanchep Syncline (west), Pinjar Anticline (central) and Swan Syncline (east). However, seismic interpretation from this investigation demonstrates that there is no folding evident in the sedimentary sequence. In contrast, Early Cretaceous and Jurassic sediments appear to dip about 10°to the east and are overlain by flat-lying Cretaceous and Cainozoic sediments. Minor normal faults within the Yarragadee Formation show vertical displacement of about 100 m.

3.2 Stratigraphy

The stratigraphic units encountered in this investigation are described in order of deposition and summarised in Table 2. Moncrieff and Tuckson (1987), and Davidson (1995) provide more regional descriptions of stratigraphical units beneath the Swan Coastal Plain. The following geological descriptions are based on field observations and lithological logging of drill samples. Detailed stratigraphic data from all monitoring bores installed during the investigation are given in Table 3.

Yarragadee Formation

The Yarragadee Formation was intersected in nine bores and was not fully penetrated. The maximum encountered thickness was 257 m in site NG9. It is unconformably overlain by a variety of formations highlighting the complexity of stratigraphy including superficial formations (NG3 and NG9), South Perth Shale (NG5 and NG14) and Gage Formation (NG1, NG4, NG6, NG8 and NG10).

East of the investigation area, it is possible that the Yarragadee Formation is conformably overlain by the Parmelia Formation. There are currently additional drilling investigations underway to confirm the extent and stratigraphic relationships of the Parmelia Formation.

Table 2 Stratigraphic sequence

Age	Stratigraphy	Maximum thickness (m)	Lithology	Aquifer
Quaternary – Late Tertiary	Superficial formations	62		
	Tamala Limestone	30	Limestone and calcarenite with minor sand and clay	Superficial aquifer
	Bassendean Sand	53	Fine- to medium-grained quartz sand with discontinuous ferruginised horizons	Superficial aquifer
	Guildford Formation	14	Sandy silt and clay, ferruginised horizons	Local aquitard
	Gnangara Sand	15	Fine- to coarse-grained quartz sand	Superficial aquifer
	Ascot Formation	29	Mostly limestone with sand and clay	Superficial aquifer
~~				
Cretaceous	Leederville Formation	198		
	Wanneroo Member	175	Sand beds (up to 30 m thick) separated by clay horizons	Leederville aquifer
	Mariginiup Member	23	Finely interbedded clay, silt and sand layers	Leederville aquifer
	South Perth Shale	21	Clay and silt with minor sand horizons	Confining bed
	Gage Formation	44	Sand, silt and clay	Yarragadee aquifer
~~				
Jurassic	Parmelia Formation	38	Silt, clay and sand	Local confining beds
	Yarragadee Formation	258	Sand, silt and clay	Yarragadee aquifer

~~~~ unconformity
~~~~

Table 3 Stratigraphic data from the North Gnangara investigation sites.

Bore	*Ground level (m AHD)*	*Base of formation below ground level (m)*										
							Kwl					
		Qt	*Qd*	*Qg*	*Qn*	*Ta*	*Kwlw*	*Kwlm*	*Kws*	*Kwg*	*Kp*	*Jy*
NG1	60.44	-	7	15	30	54	131	141	-	174	-	311*
NG2	49.95	-	27	-	33	48	138*	-	-	-	-	-
NG3	66.71	-	53	-	-	-	-	-	-	-	-	251*
NG4	59.65	-	41	-	-	53	139	147	-	183	-	305*
NG5	54.53	-	4	13	27	50	182	193	208	-	-	306*
NG6	56.62	-	3	13	-	49	185	-	-	229	-	335*
NG7	59^	-	41	-	-	51	58*	-	-	-	-	-
NG8	62.28	-	41	-	-	51	130	140	161	178	-	299*
NG9	67.67	-	53	-	-	-	-	-	-	-	-	311*
NG10	66.47	-	30	44	48	62	144	153	-	189	-	311*
NG11	42^	30	-	-	-	43	48*	-	-	-	-	-
NG12	37.39	19	-	-	-	37	111*	-	-	-	-	-
NG13	50.23	-	2	13	18	42	179*	-	-	-	-	-
NG14	52.17	-	33	-	-	54	229	252	269	-	-	311*
NGS1	63^	-	10	18	32	46	-	-	-	-	84*	-
NGS2	66^	-	18	22	35	-	-	-	-	-	61*	-

Abbreviations

Qt	Tamala Limestone	Qn	Gnangara Sand	Kwlw	Wanneroo Member	Kwg	Gage Formation
Qd	Bassendean Sand	Ta	Ascot Formation	Kwlm	Mariginiup M	Kp	Parmelia Formation
Qg	Guildford Formation	Kwl	Leederville Formation	Kws	South Perth Shale	Jy	Yarragadee Formation

* bore does not penetrate formation
^ estimated from contour map

The presence of subcropping Yarragadee Formation directly beneath the superficial formations is a major finding and is significant for understanding aquifer connectivity. At bore site NG9, there is more than 50 metres of Bassendean Sand directly overlying the Yarragadee Formation.

The Yarragadee Formation comprises interbedded sands, silts and clays. Sand beds are more common and range in thickness up to 30 m, while silt and clay horizons are generally less than 15 m thick. The sand is light grey to light greyish-brown, mostly fine-grained to granule size with gravel horizons, moderately to poorly sorted, subangular to subrounded quartz with minor white and grey feldspar grains. There are minor coloured quartz grains that can be red, orange, yellow, pink and green. Silt and clay layers are often light grey to brown (rarely dark grey to black), highly micaceous, generally soft and appear unconsolidated up to a depth of about 250 m.

The age of the Yarragadee Formation ranges from Tithonian to Callovian. It was probably deposited in a predominantly fluvatile environment with some marine influence (Backhouse unpublished reports in Pigois, 2009).

Parmelia Formation

The Parmelia Formation has been intersected in two bores (NGS1 and NGS2) at the eastern edge of the investigation area. It is unconformably overlain by the superficial formations and conformably overlies the Yarragadee Formation.

The unit comprises mostly silt and clay with a minor sand component. It typically light grey to grey in colour. The sand is mostly fine- to medium-grained, with minor coarse to very coarse grains, moderately sorted, angular to subrounded quartz with trace feldspar. There is also minor iron staining of quartz grains, mica and shell fragments. The clay is dark grey to black, firm and slightly micaceous and is interbedded with thin silt and sand layers.

Palynological analysis of the Parmelia Formation provides an age in the range of Tithonian to Berriasian (Backhouse unpublished reports *in* Pigois, 2009).

Gage Formation

The Gage Formation has been interpreted at five sites (NG1, 4, 6, 8, 10) and is up to 45 m thick. It is unconformably overlain by the Leederville Formation and South Perth Shale, and unconformably overlies the Yarragadee Formation.

The unit is comprised predominantly of sand with minor sandy clay and clay. Sand beds, range from five to over 30 m in thickness, consist of light grey to grey, fine-grained to granule sized, moderately to poorly sorted, subangular to subrounded quartz sand. There is minor white and grey feldspar, as well as coloured quartz grains ranging from reddish-orange, orange, yellow, and pink to green. The sands appear to be lithologically similar those of the Yarragadee Formation. Clay layers, up to 5 m thick, are light grey to grey with minor white and tan mottles, soft and micaceous.

The age of the Gage Formation ranges from Hauterivian to Berriasian. It was probably deposited in a shallow marine environment (Backhouse unpublished reports *in* Pigois, 2009).

South Perth Shale

The South Perth Shale has been interpreted at three sites (NG5, NG8 and NG14) in the west of the investigation area. It is conformably overlain by the Leederville Formation and unconformably overlies the Gage Formation and Yarragadee Formation.

The unit consists of dark grey to black, soft and micaceous clay. In many respects, it can be difficult to distinguish between clays from the Leederville Formation and South Perth Shale in drilling sludge samples. Though no palynology results were collected, its presence is based on geophysical logs suggesting an upwards-fining sequence (Figure 11 and Figure 12).

Leederville Formation

The Leederville Formation was intersected in all but two sites, NG3 and NG9. It was fully penetrated in seven bores with an average thickness of 120 m. The thickest sequences occur in the west. The Leederville Formation is unconformably overlain by the superficial formations, conformably overlies the South Perth Shale and unconformably overlies the Gage Formation and Yarragadee Formation.

Davidson (1995) described the Leederville Formation in terms of sandstone, siltstone and shale. In the investigation area, the sediments are largely unconsolidated to poorly consolidated, as such are more appropriately described as sand, silt and clay. The Leederville Formation is heterogeneous with a discontinuous, interbedded sequence of sand and clays. Sands beds are of variable thickness, generally thinner and finer-grained when compared with the Yarragadee Formation.

The Leederville Formation comprises three distinct lithostratigraphic units being the Pinjar, Wanneroo and Mariginiup Members. In the area, the Leederville Formation is predominantly Wanneroo Member and Mariginiup Member at the base in places. The Pinjar Member was not intersected during drilling; however, it is known to occur further west of the investigation area.

Mariginiup Member

The Mariginiup Member was intersected at six sites with a thickness of 8 to 23 m. It consists of thinly interbedded and discontinuous, grey to black, micaceous silts and clays with minor sand beds (less than 3 m thick). The sands are typically fine- to medium-grained, moderately sorted, subangular to rounded quartz with minor feldspar and trace pyrite.

It is impossible to discern the Mariginiup Member from the Wanneroo Member without geophysical logs. In the gamma ray logs, the Mariginiup Member shows a distinct and consistent fining downwards sequence (Figure 11, Figure 12).

Wanneroo Member

The Wanneroo Member was intersected at 12 sites and fully penetrated at seven sites. The thickness ranges from 77 to 175 m. It consists of discontinuous interbedded sand, clay and minor silt. Individual sand beds range in thickness from less than 10 m to more than 30 m, but are generally 15 m thick. The silt and clay layers are between 2 to 15 m thick, typically grey to black and slightly micaceous.

The sand is light grey to grey, fine- to very coarse-grained, subangular to subrounded, poorly sorted, quartz with minor white to grey feldspar. In places, grains can be granule sized with a trace of quartz grains showing iron-stained pink to reddish-orange colouration.

The age of the Wanneroo Formation is Valanginian to Aptian. It was probably deposited in a shallow marine to fluvial environment (Backhouse unpublished reports in Pigois, 2009).

The Wanneroo Formation is distinctive in gamma ray logs with alternating longer sections of low counts (sand beds) and smaller peaks of high counts (clay beds; Figure 11, Figure 12).

Superficial formations

In the investigation area, the superficial formations include Tamala Limestone, Bassendean Sand, Gnangara Sand, Guildford Clay, and Ascot Formation. Collectively, the superficial deposits range between 37 and 62 m in thickness and unconformably overlie an erosional surface on the Mesozoic sediments. In general, there is a regional trend of increasing limestone to the west and more clay to the north and east.

Ascot Formation

The Ascot Formation was intersected in all sites except for NG3 and NG9. It ranges between 10 to 29 m in thickness. The formation forms the base of the superficial formations being overlain by each of the younger superficial units, and unconformably overlying the Leederville Formation.

The unit has a variable nature comprising sand, limestone and clay with minor interbedded clays and sandy clays. There is also a wide range in colouration with grey, dark grey, light brown to yellowish brown and greenish grey. The sand is fine- to very coarse-grained but can be gravely in places, very poorly sorted, angular to subrounded quartz with minor, angular to subrounded feldspar. Accessory shells (bivalves, gastropods and tubes) and well-rounded black phosphate pebbles to 5 cm diameter are common towards the base. Glauconitic mica is often present producing a distinctive, green colouration.

The limestone (in parts marly) is generally grey, light grey to buff in colour, but can be greenish grey to yellowish-orange grey where weathered. There are varying amounts of sand are present throughout the limestone, as well as shells and phosphate nodules. The limestone can be vuggy or karstic in places with voids of up to one metre being common. At NG6, a cavernous void was encountered during drilling between 12 and 17 m.

There appears to be some reworked Leederville Formation at the base of unit. This includes Leederville-related sands cemented inside of shells and granules to pebbles of consolidated Leederville sands being entrained within the limestone.

The clays are usually soft and grey; but, can be greenish brown and brown to black in colour.

Guildford Formation

The Guildford Formation has been intersected at six sites, predominantly in the north east. It is generally thin being between 4 and 14 m thick. The Guildford Formation usually overlies the Gnangara Sand but also overlies Ascot Formation, and is unconformably overlain by the Bassendean Sand.

The formation typically comprises a clayey and sandy facies, similar to that noted by Moncrieff and Tuckson (1977). The clayey facies is generally brown to dark brown but can be green- and yellow- to orange-brown and mottled in places. The clay has variable amounts of silt and sand and is restricted to the eastern part of the study area. The sandy facies is commonly fine- to very coarse-grained, poorly to very poorly sorted, subangular to rounded quartz with varying minor amounts of feldspar, very fine heavy minerals, chert and quartzite.

Gnangara Sand

The Gnangara Sand was possibly intersected at seven sites in the north and east of the investigation area. It is up to 15 m thick and consists of white to light grey, fine- to very coarse-grained, poorly to very poorly sorted, subangular to rounded quartz with accessory feldspar and trace quartzite grains. The feldspar is typically coarser-grained than the quartz grains and is distinctively white. Where present, the quartzite grains are very coarse-grained to pebble sized. The sand commonly appears to have a bimodal grain size distribution with grains being fine-grained or coarse- to very coarse-grained.

Bassendean Sand

The Bassendean Sand is intersected at all sites except for NG12. Its thickness varies between 4 and 53 m with thickest section beneath the Yeal Reserve. The formation consists of white to light grey, fine- to coarse-grained, moderately to poorly sorted, subangular to rounded quartz sand. The quartz grains are frosted and clear. There are traces of very fine-grained heavy minerals and feldspar. Minor clayey sections and common ferruginised areas occur around current or historical water tables. The ferruginised sections are variably cemented and are commonly referred to as ‘coffee rock’.

Tamala Limestone

The Tamala Limestone was only intersected in NG11 and NG12 being the two most westerly sites. It was up to 30 m thick and comprising reddish brown to yellowish brown sand, clayey sand and silty sand over a yellowish brown weathered limestone through to light grey, silicified limestone. The limestone contains variable amounts of fine- to very coarse-grained, poorly sorted, subangular to rounded, quartz grains that are mostly frosted.

4 Developing the geological model

4.1 Selection of the 3-D visualisation package

The developing of a 3-D appreciation of the stratigraphy and geological context, as a conceptual geological model, was a major objective of the investigation. The Department of Water had limited experience in 3-D geological modelling, as such a considerable amount of time and effort was spent selecting an appropriate software package. There was also a process of trial and error with packages that proved less than successful including RockWare and Hydro GeoAnalyst.

As a result of funding from the WaterSmart Australia program, it was decided to select Schlumberger's Petrel software package. Petrel is the top of the range, most advanced, 3-D interpretation and visualisation package on the market. It is used extensively by the petroleum exploration industry.

The primary purpose of Petrel is to incorporate and combine all data captured during field exploration to build a 3-D geological model of the reservoir (or aquifer framework in the case of groundwater resources). Petrel is fully integrated with geophysical and engineering tools to allow rapid seismic interpretation and well log correlation to create 2-D surfaces, as well as real-time interpretation within a 3-D space.

4.2 Source data

More traditional sources of data included detailed lithological logs produced by a hydrogeologist; down-hole gamma and resistivity logs run prior to bore construction; and palynological age determination by Biostrat Pty Ltd. In addition to these sources, there was a wealth of new data from the shallow geophysical survey by Curtin University to be incorporated. Below is a discussion on the initial results with more detail in Curtin University (2009).

The geophysical techniques have yielded invaluable 3-D information that will improve spatial understanding of stratigraphy, as well as the distribution of the superficial, Leederville and Yarragadee Formations. The processed seismic data presents continuous geological information that clearly differentiates stratigraphy.

The stacked 2D seismic transects clearly show flat-lying superficial and Leederville Formations, while beds within the Yarragadee Formation are gently-eastwards dipping at about ten degrees (10°). There are noticeable fault structures with about 100 m displacement throughout the Yarragadee Formation, while superficial and Leederville Formations appear unfaulted. These observations would be impossible using traditional investigation methods.

Previous interpretations by Davidson (1995) and Davidson and Yu (2004) suggested the Mesozoic sedimentary sequence was folded with presence of the Pinjar Anticline and Swan Syncline. It is clearly evident from the seismic transect that there is no folding of strata. This is important finding and substantially changes the geological framework and understanding of the Perth Basin. The new interpretation is that faulting and upward block movement during continental breakup is a strong control on stratigraphic and aquifer distribution.

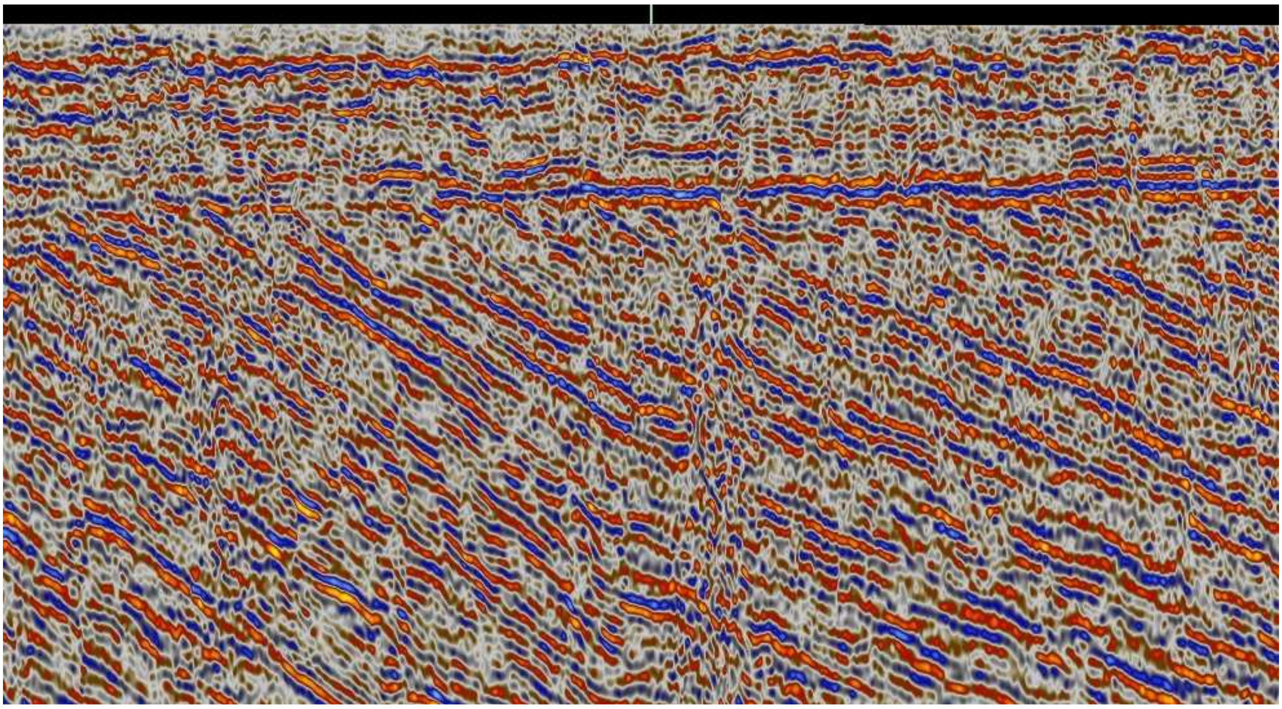

Figure 9 Example of 2D seismic data where flat-lying superficial and Leederville Formations and gently east-dipping Yarragadee Formation are evident.

Over the next six months, there will be further processing of the VSP and FWF sonic logs that may assist in better resolution of hydraulic parameter distribution. This, in conjunction with core plug analysis from NG3 (Mullen, in prep.), will lead to an improved understanding of smaller-scale variations and contribute to improved hydraulic parameter determination.

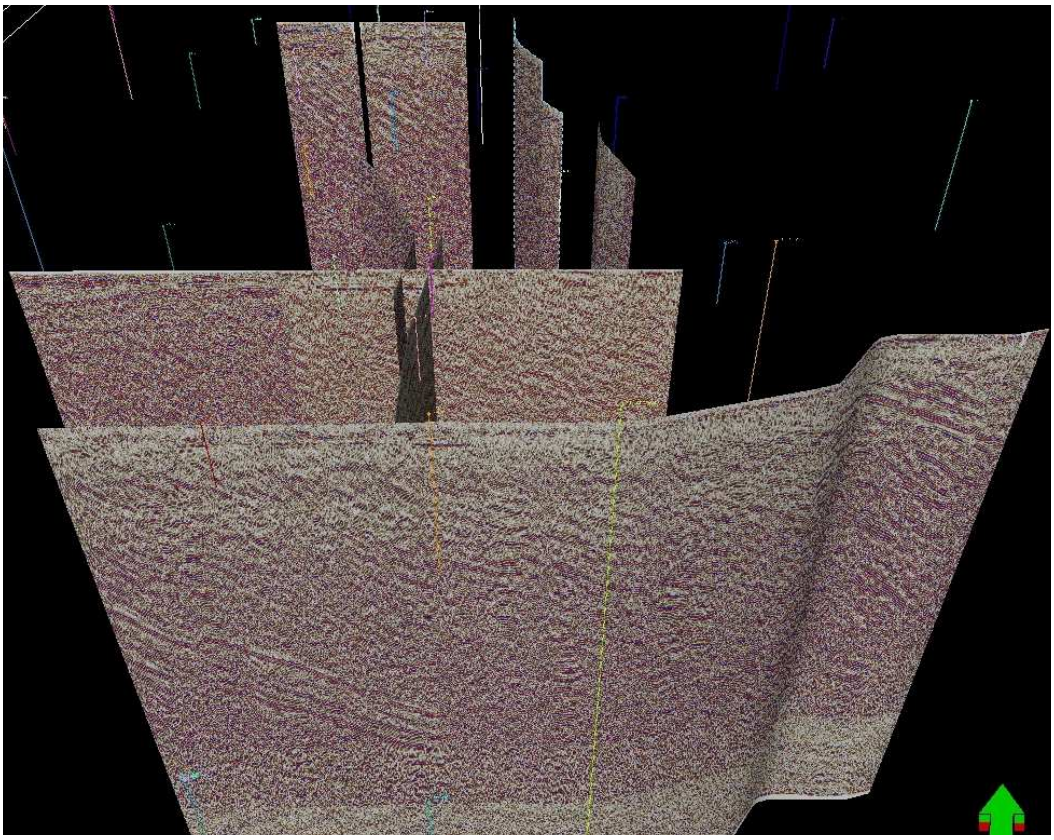

Figure 10 Screen capture of Petrel showing all the collected 2D seismic information.

4.3 Spatial 3-D interpretation

Petrel allows all data collected from the investigation to be easily imported, interrogated and interpreted from a 3-D perspective. Despite the different data formats, Petrel was able to readily import all data sets without too many problems. This included lithological logs, down-hole geophysical logs as LAS files; palynological age as selected text; and processed seismic data as SEGY files.

The most useful function in Petrel for developing an understanding between individual bore holes is well log correlation. This allows for simultaneous display of down-hole geophysics traces together with palynological interpretation and geological logs sequence (Figure 11, Figure 12). The displaying of all this information on one screen allows quicker and more precise formation boundary interpretation. This capacity to interpret in the 3-D space with all data available concurrently is a major advancement in hydrogeological interpretation.

Due to some processing delays, the seismic data from Curtin University was not initially entered into Petrel. The first geological framework was developed using the well log correlation functionality with the interpretation being confirmed by the initial processed seismic data set. The full integration of data sets has produced excellent results.

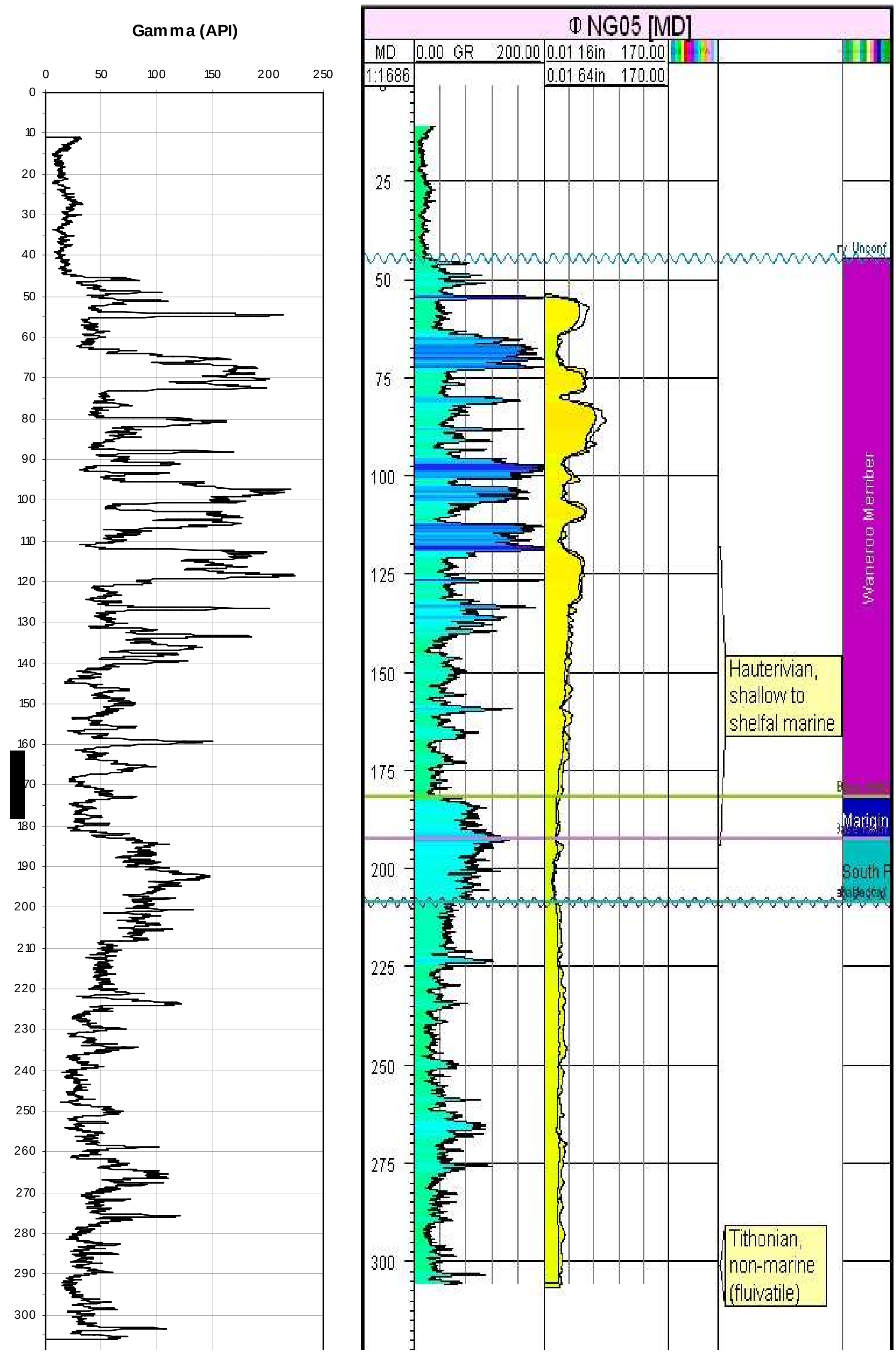

Figure 11 Comparison of Petrel geophysical log interpretation to traditional display for NG5.

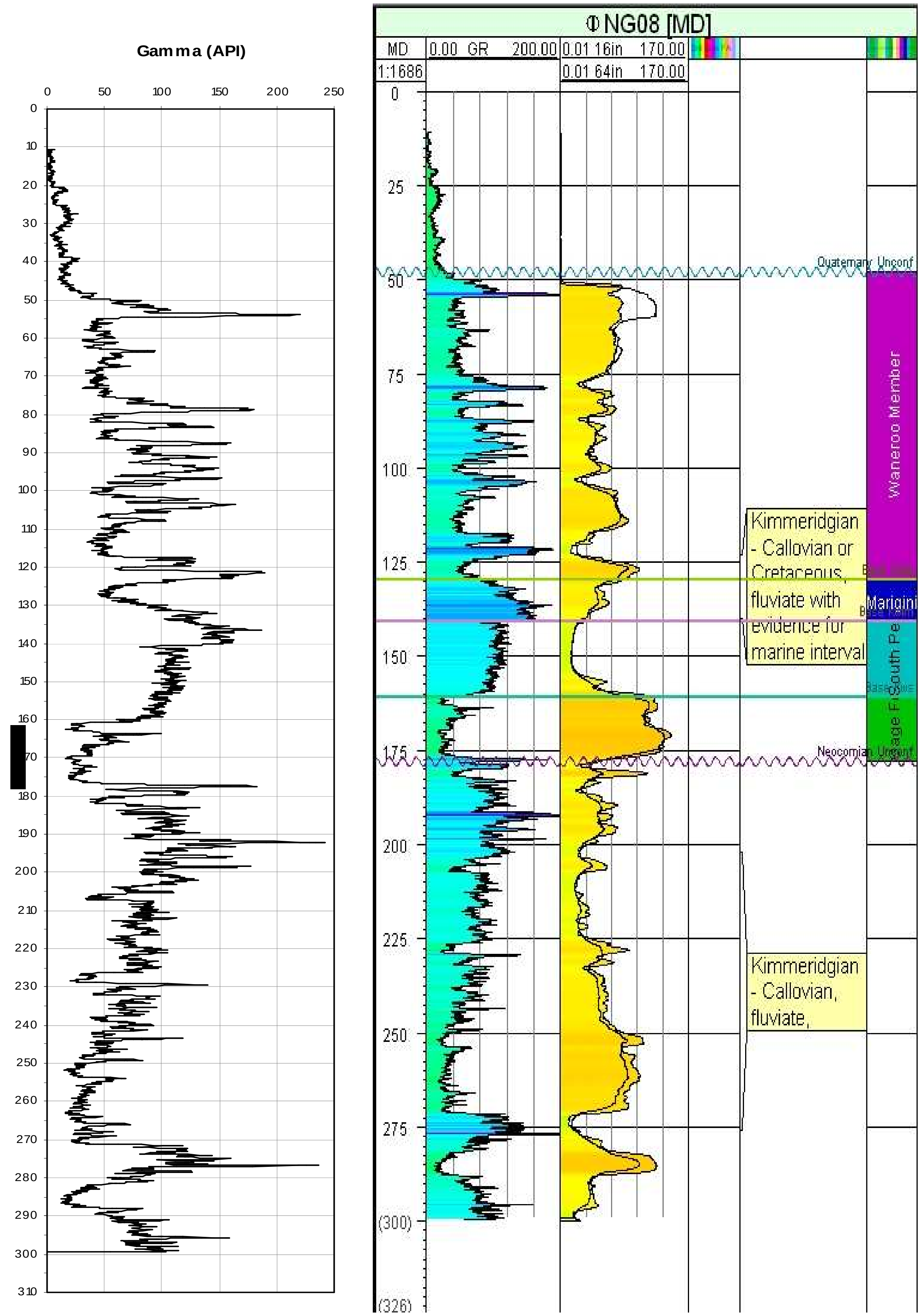

Figure 12 Comparison of Petrel geophysical log interpretation to traditional display for NG8.

4.4 Preliminary conceptual geological model

The 3D spatial presentation of data in Petrel is unparalleled, when compared with previous investigations. Geological interpretations are considerably simpler and more robust. It has been possible to generate a full 3-D appreciation of the stratigraphy in the northern Gnangara Mound.

Despite the need for ongoing work, there have been a number of major findings and improvements in the geological interpretation. This has potential to substantially change previous understanding of the hydrogeology. It is attempted to highlight the most significant findings and present some initial interpretations.

Stratigraphic relationships

The well log correlation function in Petrel has proved extremely useful in making interpretations between individual bore holes. The simultaneous display of down-hole geophysics traces together with palynological interpretation and geological logs has produced meaningful correlations. Figure 13 shows a screen-shot from Petrel showing the well correlation functionality in 3-D.

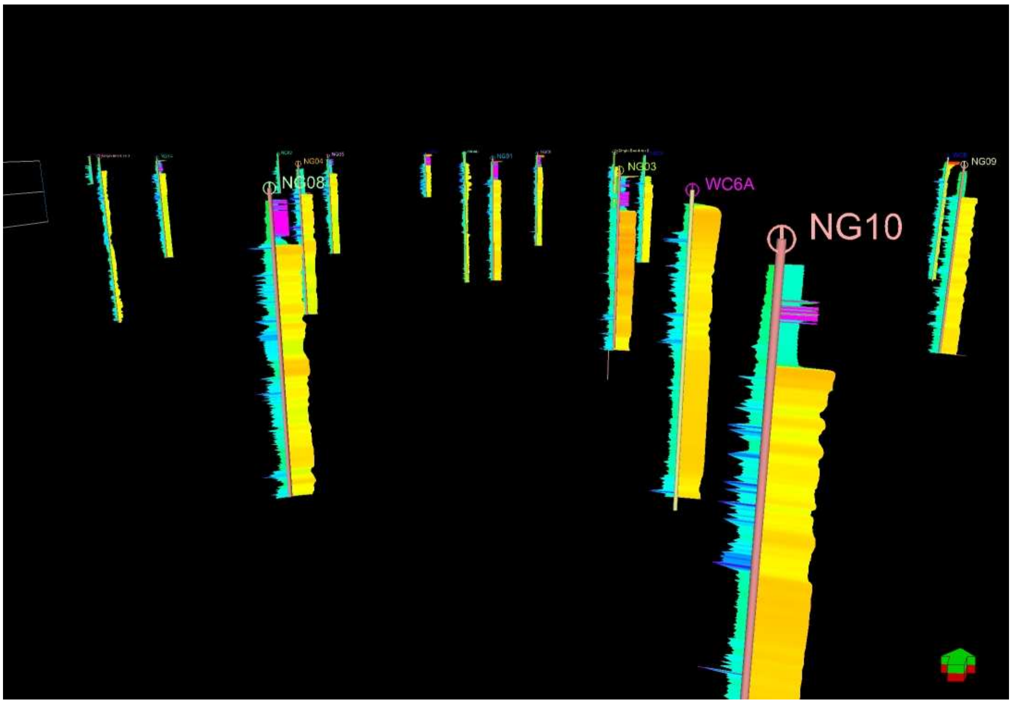

Figure 13 A screen-shot from Petrel showing 3-D well correlation functionality.

This interpretation between holes has resulted in the ability to generate 3-D formation surfaces (Figure 14) and provide the raw data that can be used to generate cross section (Figure 15). The rapid generation of cross section is extremely useful for determining stratigraphic relationships.

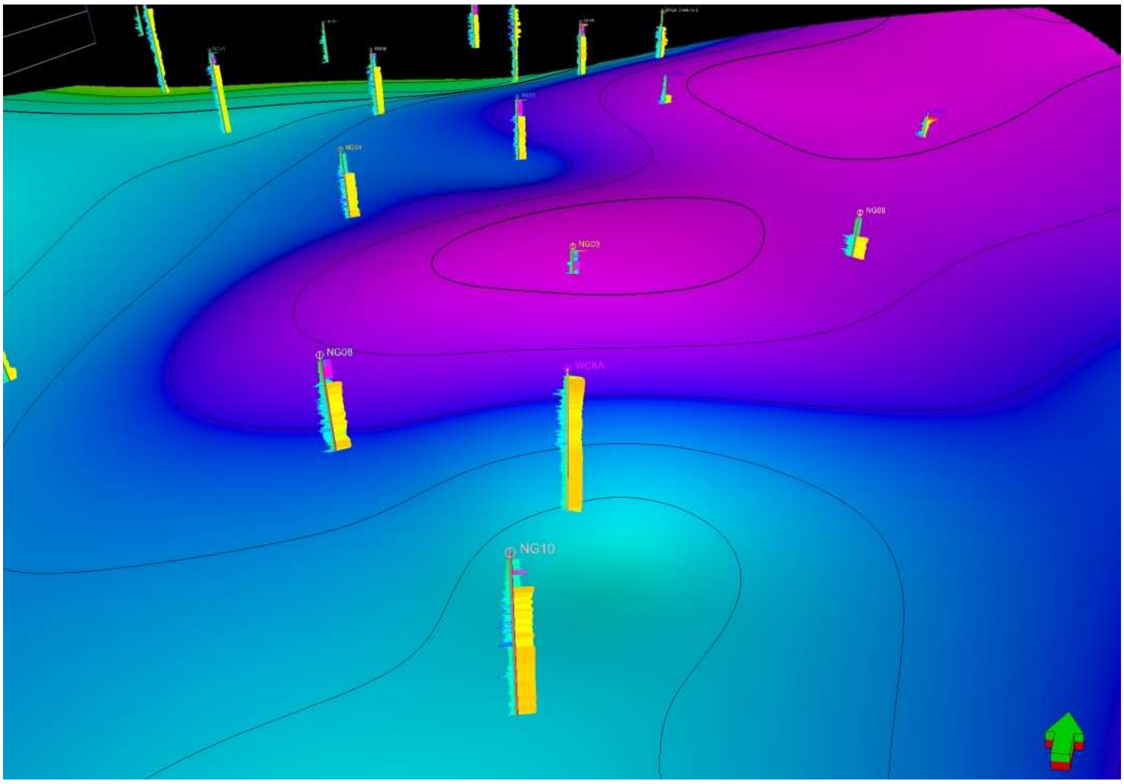

Figure 14 A screen-shot from Petrel showing 3-D formation surfaces created from formation picks on well logs.

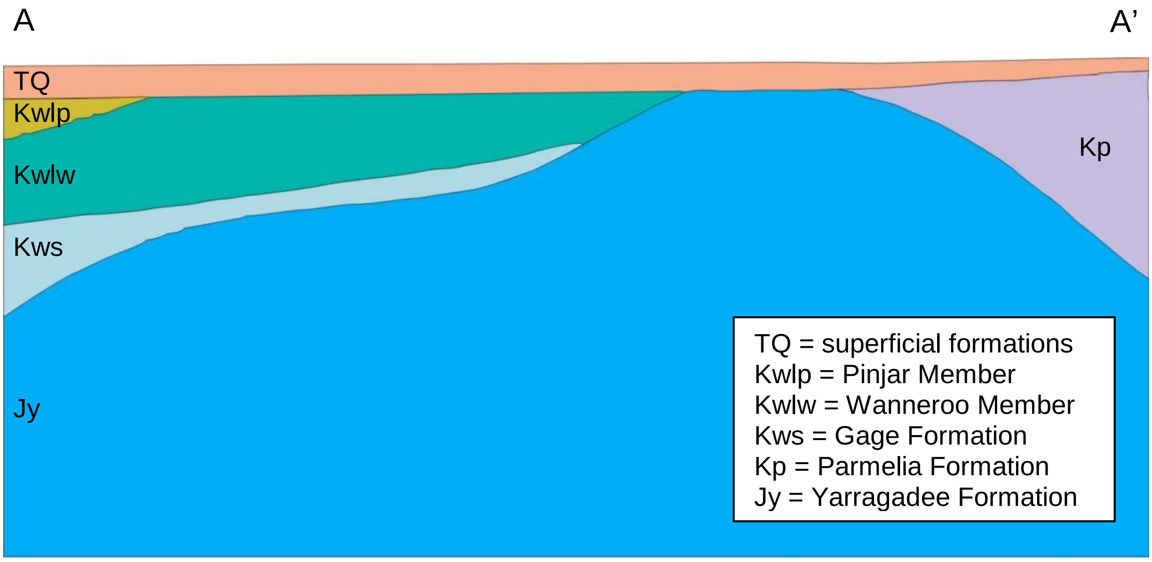

Figure 15 Schematic geological cross section through the study area.

Hydraulic window

Confirmation of the hydraulic window by Davidson and Yu (2004) is a significant finding. Rather being a small window comprising Wanneroo Member of the Leederville Formation sitting directly on the Yarragadee Formation (Figure 16), there is actually more direct connectivity with superficial formations sitting directly on Yarragadee Formation (Figure 17). In addition, there is also a larger window of

Wanneroo Member within the Leederville Formation subcropping beneath the superficial formations.

Figure 17 shows the lateral extent of sub cropping Yarragadee Formation, as well Wanneroo Member of the Leederville Formation, beneath the superficial formations. This has important ramifications from a hydrogeological perspective, when evaluating groundwater recharge into the Yarragadee aquifer, as well as changes in water levels and propagation of drawdown impacts related to confined aquifer abstraction.

The new subcrop interpretation is quite different to that presented by Davidson and Yu (2008). This can be seen by comparing Figures 16 and 17, which shows a previously unidentified area of subcropping Yarragadee, and a more extensive area of subcropping Wanneroo Member.

Faulting

As mentioned previously, the new observation of faulting rather than folding being the dominant structural control of aquifer distribution is a major finding. This has major ramifications for understanding stratigraphic and hydrogeological relationships throughout the whole Perth Basin.

Parmelia Formation

The Parmelia Formation in the east appears more extensive than previously thought. When combined with Yarragadee Formation, it appears to disconnect the Leederville Formation. The disconnection within the Leederville Formation is an important observation as it implies there are two separate groundwater flow systems within the Leederville aquifer in this part of the aquifer system. This will have implications for improved conceptualisation of PRAMS in this area.

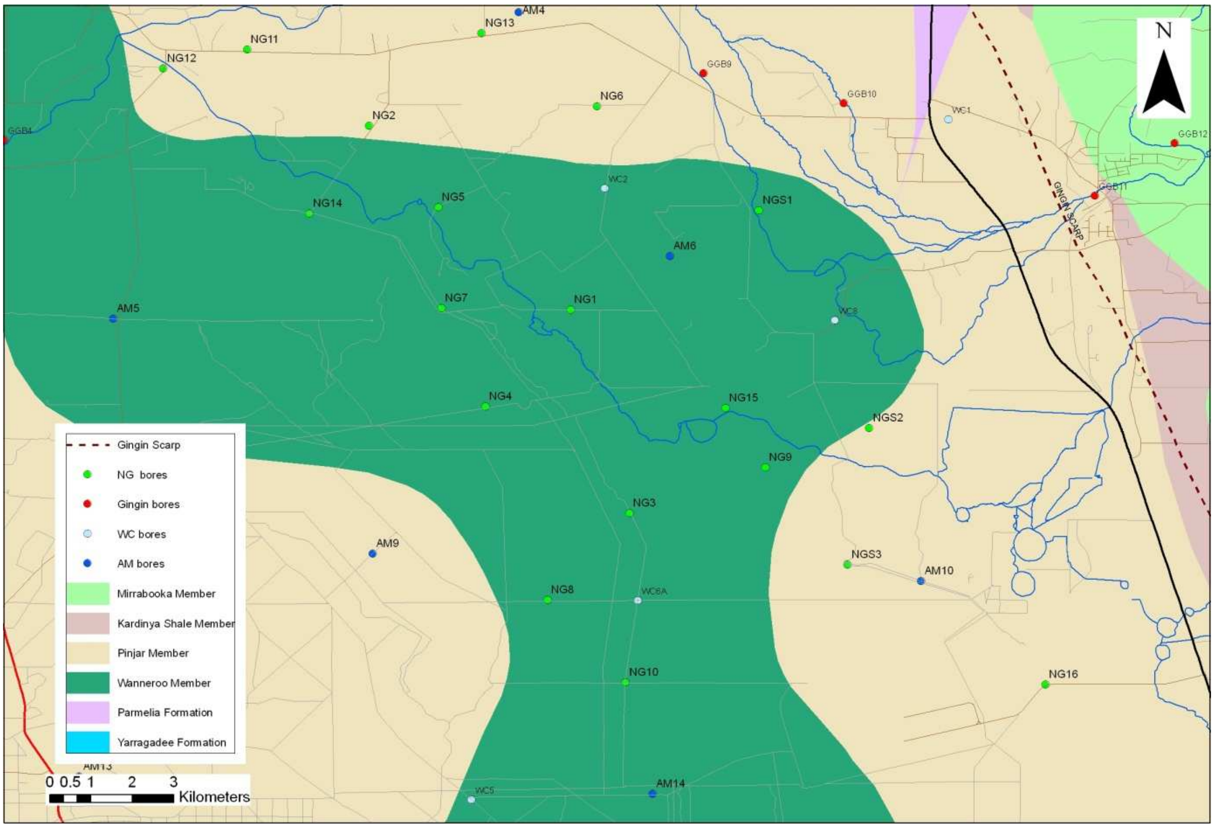

Figure 16 Subcrop interpretation map at the base of the superficial formation (after Davidson and Yu, 2008).

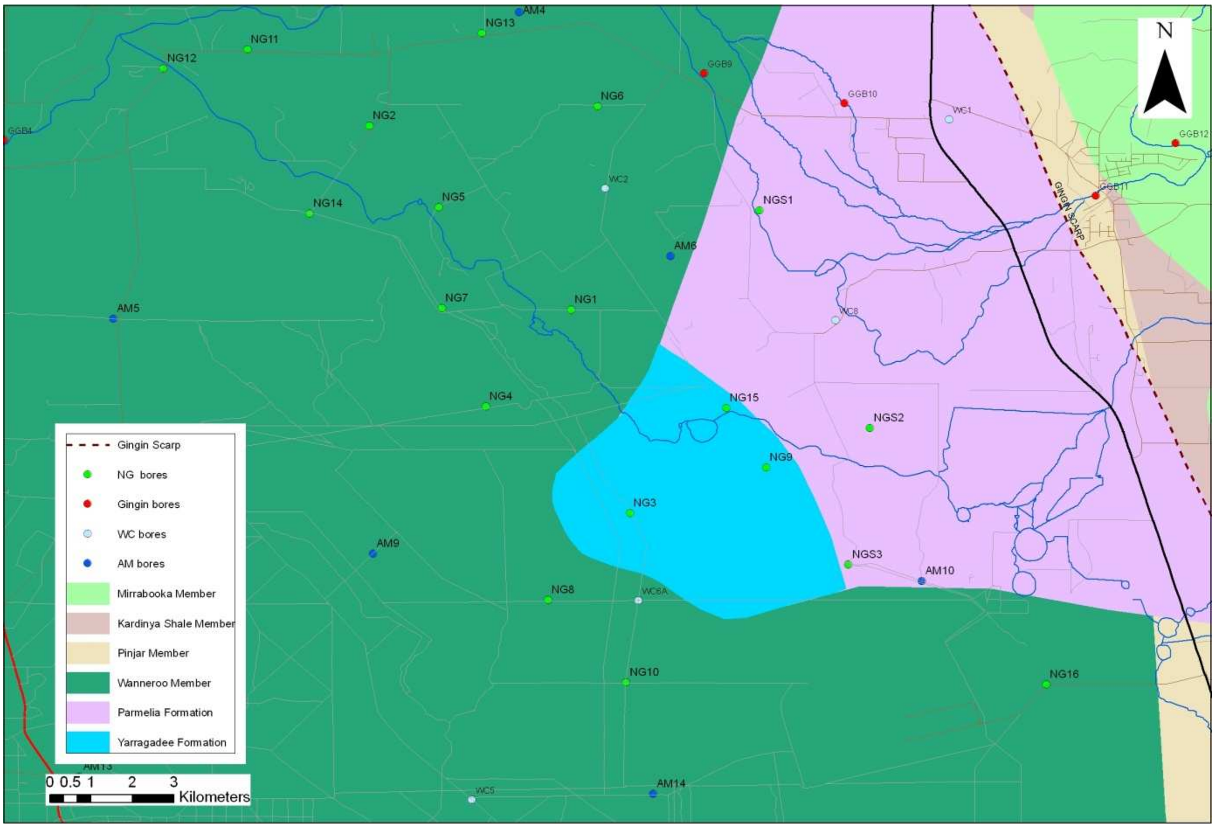

Figure 17 Current subcrop map at the bottom of the superficial formation based on information from this investigation.

5 Conclusions

The Gnangara North investigation is the most extensive and innovative undertaken by the Department of Water. This has been only possible by close collaboration with Water Corporation and Curtin University. The contribution of funding by the Australian Government's under Water for the Future's – Water Smart Australia program has meant that a more thorough investigation was possible.

As part of the investigation, 65 monitoring bores were installed into the superficial, Leederville and Yarragadee aquifers. Of these, 49 have permanent water level loggers installed to record six-hourly levels. The new monitoring bores and increased measurement frequency will assist in resolving declining water levels across the investigation area.

In order to improve the conceptual model, a shift from collecting 2D to 3D information required the integration of new, innovative techniques with more traditional investigations. More than 50 km of seismic transects were collected by Curtin University to further improve the spatial understanding of stratigraphy. This new research has successfully collected valuable information from the surface to 1000 m below ground level. Water chemistry samples, down hole geophysics, palynology and isotopic tracer analysis (for age dating) were also applied.

Petrel, a petroleum industry software package, was selected to incorporate all data collected from the investigation to be easily imported, interrogated and interpreted from a 3-D perspective. This spatial presentation of data is unparalleled, when compared with previous investigations. Geological interpretations are considerably simpler and more robust. It has been possible to generate a full 3-D appreciation of the stratigraphy in the northern Gnangara Mound.

Results of the investigation have increased the understanding of the geology. Most importantly, the hydraulic window from the unconfined superficial aquifer to the Yarragadee aquifer has been delineated. Seismic results have demonstrated that there is no folding of the stratigraphy with faulting to be a more important structural control. The Parmelia Formation appears to subcrop near the Gingin Scarp, which effectively separates the Leederville Formation into two distinct entities.

These findings are crucial to creating a more accurate and robust conceptual model for the numerical PRAMS model. Ultimately, these findings will allow DoW to better manage the groundwater resources of the Gnangara Mound with an improved PRAMS model that will lead to improved allocation limits for sustainable abstraction.

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