APPLICATION OF MAGNETIC RESONANCE DATA FOR GROUNDWATER PROSPECTIVITY IN THE FITZROY BASIN, WESTERN AUSTRALIA

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SUMMARY

In the Fitzroy Basin of Western Australia, both ground and borehole Nuclear Magnetic Resonance (NMR) techniques have been applied during a groundwater prospectivity assessment of the Cenozoic sediments, and the Palaeozoic and Mesozoic sandstone aquifers. Ground magnetic resonance (GMR) data was acquired at ten sites from the within the basin and the data was inverted to obtain estimates of the one-dimensional water content for the top 100m. Where these sites were co-located with boreholes, the results were consistent with inverted borehole NMR data and other litho-stratigraphic information although with a reduced horizontal resolution.

Both the GMR and borehole data suggest that the Palaeozoic Grant Group and Poole Sandstone have high water content and have the potential to be highly productive aquifers. Furthermore GMR can be used estimate the depth to water table for unconfined aquifer, using 5 volume % as the threshold for saturated zone.

Key words: Fitzroy Basin, AEM, GMR, NMR, groundwater.

INTRODUCTION

The Western Australia Fitzroy Basin is one of the few agriculture districts in the Kimberley, mainly for cattle grazing with minor stock-feed irrigation. The Western Australian Government's 'Water for Food' program (Harrington and Harington, 2015) aims to lift agricultural productivity and encourage capital investment within the Fitzroy Basin with a focus on a number of sub-areas including Derby-Mowanjum-Knowsley; May-Meda River; Fitzroy Crossing-Go Go; Willare-Lower Fitzroy River; Oscar Ranges and Mount Anderson (Figure 1). WA Department of Water was tasked to investigate the groundwater resources of the Fitzroy Basin.

Groundwater investigations in remote areas such as the Fitzroy Basin face challenges including the high cost and difficulty in obtaining drilling permit due to lengthy heritage and environmental approvals processes. Non-ground disturbing geophysical techniques, including airborne electromagnetics (AEM), ground magnetic resonance (GMR) and borehole Nuclear Magnetic Resonance (NMR) offer a more practical, cost-effective alternative approach to estimate key hydrogeological parameters including depth to water table, porosity and transmissivity without the need for costly, lengthy approvals.

Under the auspice of 'Water for Food' program, time-domain AEM data were acquired in 2015 across a large area within the basin (Figure 1). Field data acquisition activity took place in September to November 2016 to obtain borehole induction conductivity, natural gamma, NMR and slug tests. Due to the diameter of the different geophysics tools and slug, a complete data set can only be acquired from PVC cased bores that are 100mm in diameter; 50mm diameter PVC cased wells have induction conductivity and natural gamma logs only. In all, induction and gamma data were acquired for 41 bores, NMR data were acquired for 11 bores (Figure 1) and a few bores have been slug tested. GMR data were also acquired at 10 sites, with 6 sites proximal to monitoring bores (Table 1).

This paper summarises the GMR free and bound water contents and, where borehole geophysical logs are available, compare against the NMR data and geological bore logs to evaluate the GMR data, in particular to sense the water table of unconfined aquifer and deduce the effective porosity of aquifer.

HYDROGEOLOGY

The Fitzroy sedimentary basin is in general a broad syncline, i.e. older strata on the edge of basin and younger units in the middle or NW along the plunging fold axis. The sedimentary units span from Late Carboniferous to Neogene-Palaeogene, comprising terrestrial sandstone, siltstone and shale. The basal sedimentary unit is the Late Devonian Fairfield Group comprising limestone, sandstone and siltstone (Mory and Hocking, 2011). The main aquifers include the Permian-Carboniferous Grant Group (sandstone), Early Permian Poole Sandstone, and the Jurassic Wallal and Erskine Sandstones. Main aquitard includes the Permian Noonkanbah Formation and Triassic Blina Shale. A large part of the basin is occupied by the Permian Liveringa Group, which consists of mudstone, sandstone and carbonates, and may be an aquifer to a local extent (Harrington and Harrington, 2015).

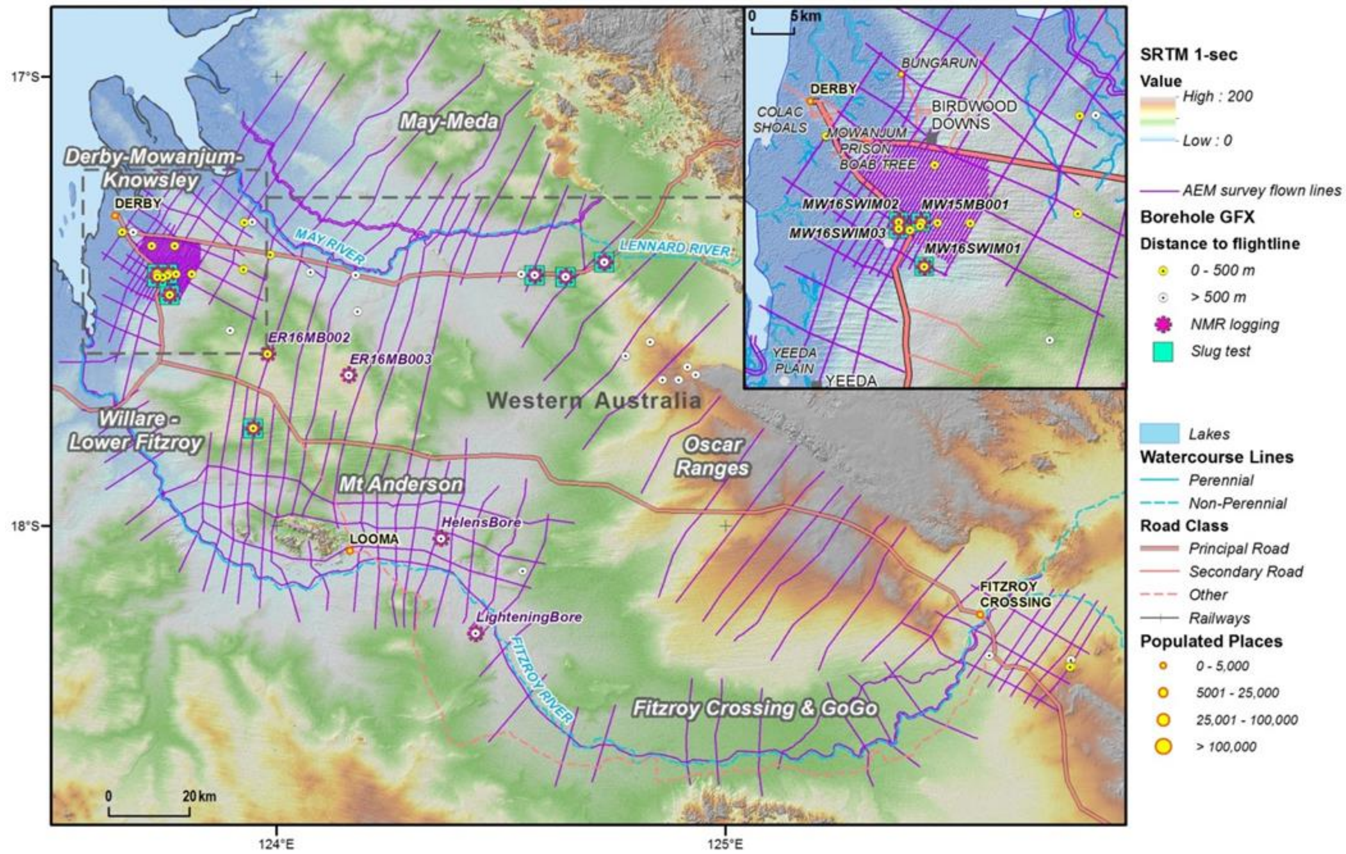

Figure 1. Fitzroy River Basin study area showing localities, AEM flight lines, and wells with induction conductivity, natural gamma and NMR data. Background is pseudo-coloured 3 arc seconds SRTM DEM. Note. Kimberley Downs are proximal to Lennard River.

Table 1. GMR data acquisition site locations.

Derby-Mowanjum-Knowsley	*Mount Anderson*	*Kimberley Downs*	*Willare-Lower Fitzroy*
MW16MB002	MA15MB001	KD16MB001	(AEM Lines) 60000,1600101, 600201
MW16SWIM003	MA15MB004	KD16MB002	Jowlaenga

METHODS

Time-domain AEM data were acquired in 2015 using SkyTEM-312 system. Following some initial processing, inversion and interpretation of the AEM data a field geophysics program was undertaken in October-November, 2016. The program included the acquisition of GMR, borehole induction, natural gamma, borehole NMR and slug tests data with the diameter of the geophysical tools and slug meaning that a full suite of borehole geophysics could only be undertaken on 100mm diameter PVC bores. In total, induction and gamma data were acquired for 20 bores, NMR data were acquired for ten bores while GMR data were acquired from ten sites distributed across the basin.

The GMR system deployed was from Vista Clara Inc. and includes a DC-DC converter, a transmission and a tuning unit. The system was powered by two 12V batteries in series. To detect potentially deeper water table and aquifer, the transmission loop at each site was set up as 100 m square with 60 ms excitation pulse (Table 2). The transmission loops were parallel with the local magnetic field's declination angle (~ 2.00º to 2.20º). At each site, a 60m square reference loop was deployed at approximately 100 m away from the transmission loop to monitor and where applicable reduce noise levels. The GMR data were acquired using Free Induction Decay (FID) method with a full description of the acquisition settings and parameters listed in Table 2.

From the GMR data, cultural and ambient noise were typically low although when afternoon thunderstorms were present within the region, the noise levels were greater than the GMR signal of ~ 500nV. Noisy data were manually removed from each stack during processing and a threshold of 33 ms T_2^* was used to demarcate between 'bound' and 'free' water contents. As borehole and AEM data acquired adjacent to the GMR sites indicated that the conductivity of the subsurface was low (>100 mS/m, or <10 Ωm), a resistive model was during inversion of the GMR data. The data were modelled to 100m depth, with depths of investigation ranges from 80m to 90m although the resolution generally began to decline at around 70m depth (Figure 2).

Table 2. GMR acquisition parameters and settings.

Magnetic Field Intensities	49640 nT – 49650 nT	GMR Method	Free Induction Decay (FID)
Declination angle	2.00º – 2.18º	Recovery time (Tr)	6 seconds
Inclination angle	-47.4º - -47.5º	Maximum pulse moment	20 ms
NMR Frequencies	2114 Hz – 2131 Hz	Pulse Moment Range	200
Transmission Loop Size	100m by 100m square	Tuning Capacitance	7 µF – 8 µF
Reference loop Size	60m by 60m square, 100m lead out	Data Stacks	12 to 15

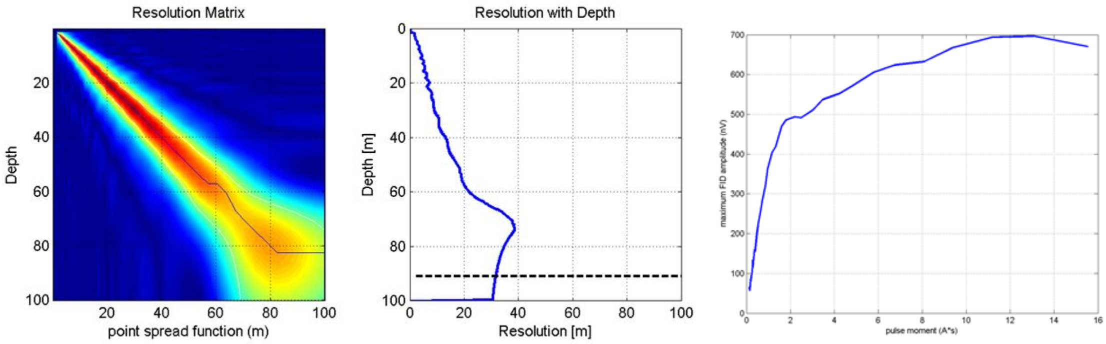

Figure 2. Examples of data attributes and resolution diagrams during from inversion model.

RESULTS

Borehole NMR data, acquired at half metre interval, provide high resolution information on the water content within the close vicinity of the bore. For example, the NMR data at monitoring bore KD16MB001 show that the bound and free water contents correlate well with the lithological information described from drill samples at 1 m interval (Figure 3). Natural gamma logs also correlates well with lithology, with higher gamma counts for shale and mudstone, and lower gamma for sandstone. The NMR derived hydraulic conductivities (K) of the saturated zone were calculated using Schlumberger-Doll-Research (SDR) equation with lithology-based formation factor 'C' (Lawrie *et al.*, 2012). Within the screened interval, the K_{SDR} values are within half order of magnitude compared to the slug test derived K (*i.e.* depicted by the vertical green line in Figure 3 under the K_{SDR} column).

GMR is a ground technique and hence a large transmission loop (100m) was required to measure the NMR response at depth. Hence the technique measures the water content of a larger volume of rock compared to the borehole NMR resulting in a smoother water contents profile. Figure 3 depicts a site from which a large suite of data was collected including geophysics and lithological descriptions. In this area the free water content increases at a depth of ~65m which is consistent with the occurrence of more transmissive sandstone. The GMR free water of ~ 20 vol. % (with 5 vol. % bound water) is slightly lower than the NMR free water (~ 25 vol. % to 30 vol. %). This difference may be due to the two techniques measuring different volumes of the aquifer or alternatively a minor adjustment of the T_2^* threshold from 33 ms to 30 ms may better reconcile the free water contents. For the near surface interbedded shale, mudstone and sandstone, GMR data were not able to demarcate the variations in water contents. For estimating water content within thin (*i.e.* 5-10m) units within the near surface, a smaller transmission loop size of 60m square and 40 ms excitation pulse may be better suited.

The standing water level (SWL) of bore KD16MB001 is was measured at 14.4 m depth (Figure 3). Despite the presence of some near-surface interbedded shale mudstone and sandstone, we consider the Poole Sandstone as an unconfined aquifer and as such, the SWL is considered to be the water table. At the water table depth, the borehole NMR free-water is between 5 vol. % to 10 vol. % whereas GMR free-water is at 5 vol. %. This suggests that GMR free-water of 5 vol. % can be used to estimate the water table in a profile where water content increases with depth.

CONCLUSIONS

In this study, both borehole NMR and GMR data are consistent with lithological descriptions. The borehole NMR data, sampled at half metre interval, is of higher resolution compared to GMR data. The GMR data acquired using 100 m square loop with 60 ms excitation pulse is adequate to detect the presence and estimate basic properties of shallow aquifers. However, to detect deeper aquifer between 80 m to 100 m would require a larger current and may thus necessitate a second DC-DC converter and an increase in excitation pulse to 80 ms or 100 ms. To detect near surface interbedded aquifers, a smaller transmission loop with lower excitation pulse of 40 ms would be better suited.

In this study we found that using 5 volume % as the threshold for saturated zone yielded estimates for the water table that were in agreement with standing water levels measured at nearby bores. Sandstone aquifers such as the Poole Sandstone has high free water content (20 - 25 vol. %) in the NMR logs, but only 15 - 20 vol. % in GMR profile. Bound water is classified as T_2^* of <33 ms, and fine tuning this threshold may provide better depiction of free water, which is a surrogate for effective porosity and the main determinant in the hydraulic conductivity calculation of an aquifer.

Whilst NMR data acquisition is constraint by accessible bores with optimal casing diameter and construction material, GMR allows much more spatial freedom, but in our experience it still restricted to access tracks and properties. As a 1D sounding technique, GMR data can provide valuable information on the aquifers' hydrogeological properties when many sampling locations targeting specific aquifers are carried out.

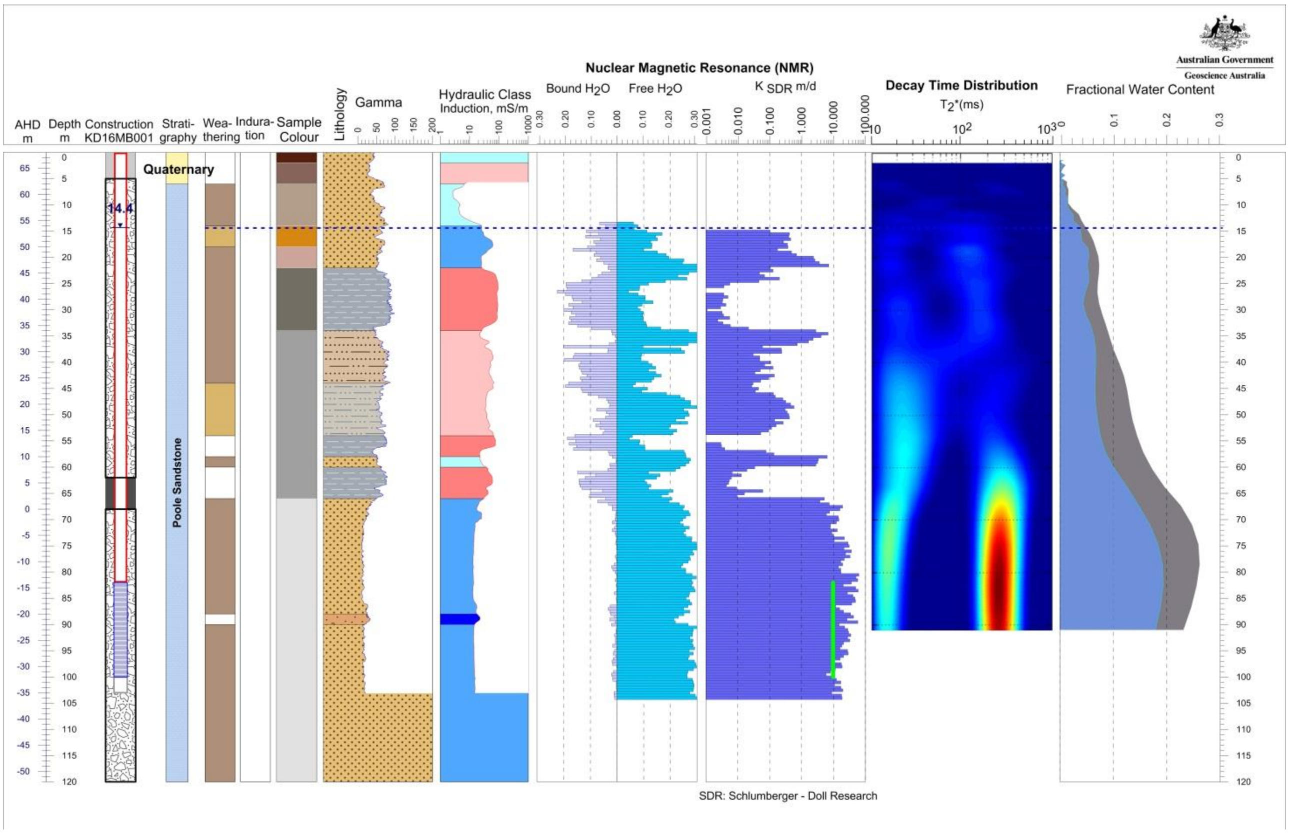

Figure 3. Borehole litho-stratigraphic log with induction conductivity, natural gamma, NMR- bound and free water and calculated hydraulic conductivity information, together with GMR decay time distribution and fractional water contents in the columns to the right.

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