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Using borehole NMR data to determine the effective porosity and estimate the groundwater resource of a shallow semi-confined aquifer, western New South Wales, Australia.

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SUMMARY

Estimating groundwater storage volumes is important for assessing the potential capacity and recovery efficiencies of Managed Aquifer Recharge (MAR) strategies. However such volume estimates are vexed by poor characterisation of factors such as the effective porosity of the aquifer. These issues were faced by the Broken Hill Managed Aquifer Recharge (BHMAR) project which aimed to define key groundwater resources and aquifer storage options in the lower Darling River floodplain of western New South Wales, Australia. The project was multi-disciplinary and utilised airborne electromagnetics (AEM), borehole nuclear magnetic resonance (NMR), LiDAR DEM data, and lithological, hydrostratigraphic, and hydrochemical information to develop a suite of hydrogeological and groundwater property maps and products.

Part of the BHMAR project was a study to determine if the NMR free-water data depicts the effective porosity of the sediment and could be used in a workflow to estimate groundwater storage volumes in the target aquifer.

In 2011, 29 sonic drilled bores were logged using the Vista Clara Javelin system operated at single frequency (245 kHz) and 2.25 ms echo spacing. Ten bores were re-logged in 2013 using the improved system with dual frequency (245 kHz and 290 kHz) and shorter echo spacing (1.5 ms). An investigation ensued to validate these NMR results. This included examination of the NMR data processing parameters and optimal regularization factor, additional matric potential and gravimetric water experiments to determine the fractional water and total porosity of sediment, and inquiring into the magnetic susceptibility and mineralogical composition of the sediments. It was concluded that a calibration error in the Javelin tool had caused the detected lower water contents in the 2011 data. A linear factor of 1.2 was applied to rectify this issue. The laboratory experiments showed comparable results to the NMR free-water and total water for sand and muddy sand, but the NMR underestimated the total water in mud. Having established that NMR free-water is a surrogate for effective porosity, the lower and upper quartiles of the NMR free-water (recalibrated 2011 data set) for each of the five hydraulic texture classes were used to estimate the groundwater storage volumes in the target aquifer.
Key words: Borehole NMR, effective porosity, matric potential.

INTRODUCTION

Estimates of groundwater storage volumes are used in groundwater resource assessments, particularly in the context of the potential for Managed Aquifer Recharge (MAR) strategies. In the lower Darling River floodplain of western NSW, Australia, the Broken Hill Managed Aquifer Recharge (BHMAR) project was tasked with identifying potential groundwater resource or aquifer storage targets for drought security purposes (Lawrie et al., 2012a). To achieve this goal, a comprehensive suite of data was acquired, including airborne electromagnetics (AEM), a LiDAR digital elevation model, borehole electrical conductivity, natural gamma and nuclear magnetic resonance (NMR) logging, lithology and hydrochemistry.

Groundwater storage estimates require robust characterisation of effective porosity for the aquifer of interest. As part of the BHMAR project, the NMR free-water data was assessed as a possible surrogate for effective porosity, to be incorporated into groundwater storage estimates for the target aquifer.

METHOD AND RESULTS

Borehole NMR data were acquired at 29 sites across the BHMAR area in 2011 using the Javelin system by Vista Clara. Data was collected from the surface to ~70 m depths at 0.5 m interval to account for the generally thin (≤ 2m) sedimentary layers and the variability in porosities. The 2011 Javelin system operated with a single frequency at 245 kHz and an inter-echo spacing of 2.25 ms (Table 1). Field test shows that a recovery time of 4 seconds was sufficient to detect the water contents in the sediments but 5 seconds recovery time was selected to log bores with thick gravely coarse sand sequences in the main semi-confined aquifer. In 2013, an improved system was available with shortened inter-echo spacing of 1.5 ms and data were sequentially collected at two frequencies (245 kHz and 290 kHz) (Table 1). This expands the detection space around the bore annulus from 2 mm to ~10 mm thick shell at ~19 cm from the centre of the tool (Vista Clara, 2013). A smaller program of 10 wells were re-logged in 2013 using the improved system to check for consistency in the effective and total porosity measurements in the 2011 data and to identify any observable calibration issue or magnetic effect.

In both 2011 and 2013 surveys, calibration checks were conducted by submersing the tool into a tank filled with fresh water. The electrical conductivity of the water does not affect the signal unless the water is greater than 1 S/m (Vista Clara, 2011), which is absent in the project wells. In the 2011 field calibration check, due to the length of the probe being slightly higher than the water tank and not fully submersed, only 86 ±7 vol. % total water was detected. Subsequent check conducted for the 2013 logging program where the tool was fully submersed return 100 ±3 vol. % water, indicating that the tool was calibrated.

Table 1. Operator settings of the BHMAR project NMR logging program.

Operator setting	2011	2013
Probe ID	JP250G	JP250G
Operating mode	245 kHz	245 and 290 kHz
Recovery time	4 - 5 s	4 s
Echo train	70 µs	70 µs
Inter-echo spacing	2.25 ms	1.5 ms
Number of averages	100	100
Probe quality factor	~53	~53

The Javelin data files were processed using the Javelin Log Processing program, which extracts, filters, and scales the spin echo signals, conducts noise cancellation and removes impulse noise (Vista Clara, 2011). The software implements an inversion of the Carr-Purcell-Meiboom-Gill (CPMG) pulse sequence decays (Coates et al., 1999) to solve for a T_2 distribution. Based on user inputs for T_2 cut-offs, the software calculates total water, free-water (at 33 ms), capillary-bound water (at 3 ms) and clay-bound water (at 0.3 ms) (Vista Clara, 2013).

It was found that the noise (5 %) in the upper part of the log at depths shallower than 25 m is higher than the noise (3 %) at greater depths. However, the processing software only takes one regularization factor for the complete inversion run. Too high a regularization factor will tend to smooth the T_2 decay function and lower the amplitude of the signal resulting in lower fractional water contents. If the regularization is set too low, the inversion tends to fit the noise, with resulting T_2 distribution having high-frequency noise in the curves of free-water, bound-water and T_{2ML}. A series of inversions were tested by varying the regularization factors from 1 to 100 and the optimum regularization factor of 5 was selected to reprocess the 2011 and 2013 data sets.

Of the 29 sites, 26 wells were drilled using a sonic coring technique and 3 wells by mud-rotary method. As the NMR tool measures a zone close to the annulus any disturbance or changing of the material may cause variations in the NMR measurements. Comparing the two techniques, bores constructed from mud-rotary method are more susceptible to the introduction of drilling mud into the formations, and also washout, where loose in-situ materials surrounding the bore annulus were removed and later replaced by materials during well construction. The results from mud-rotary drilled bores were found to be consistently lower in factional porosities compared to nearby sonic drilled bores. Thus, data from the three mud-rotary wells were not used for further investigations.

A set of laboratory tests were conducted on the sonic-drilled sediment cores and intact materials encapsulated in Lexan core lining. These experiments aim to determine the magnetic susceptibility and mineralogical composition of the sediment, in particular the presence of ferruginous minerals and phyllosilicates (i.e. clay). Gravimetric water content (oven drying of wet sediment at 105°C) and matric potential experiments were carried out to compare with the NMR derived free-water and total water.

Cores from two representative sites were selected for magnetic susceptibility tests. The magnetic susceptibility ranges from 1 to 5356 (x 10^{-5}) SI, with median of 573 x 10^{-5} SI. Though this limited finding is inconclusive to support the influence on T_{2ML} value, the occasional occurrence of magnetic minerals cannot fully account for the consistently low fractional water. Mineralogical identification using X-ray diffraction and hyperspectral analysis of the core samples showed the presence of goethite and haematite in the aquifer sequence (Lawrie et.al., 2012b). Iron coatings on sand grains can influence the surface relaxation rate and shorten the decay time, but would unlikely decrease the amplitude of the signal and underestimate the water contents. Short wavelength infrared (PIMA) analysis on several core materials suggests the presence of clay in the main aquifer. The clay present includes kaolinite and montmorillonite (shrink-swell) (Lawrie et al., 2012b). The existence of iron-rich coatings on sand grains and non-quartz minerals in clastic sediment affect the surface relaxivity and the internal field inhomogeneity (Chen *et al.*, 2011). The overall impact is to decrease the T_2 distribution in time, and lower the T_{2ML} values. There is a clear correlation with the impact of clay, montmorillonite in particular, on the NMR results but decoupling that from continuous NMR logs without detailed mineralogical information would be difficult.

Fourteen sedimentary textures were identified from the sonic cores and grouped into five main hydraulic texture classes, namely mud, muddy sand, fine sand, medium sand and gravely coarse sand.

A total of 425 gravimetric water content measurements were undertaken on selected samples of the BHMAR sonic cores in the saturated zone. These data were acquired within two months of the cores being collected. As these are expressed by mass, they need to be divided by the particle density (quartz 2.65 g/cm^3, kaolinite ~2.6 g/cm^3 and montmorillonite ~2.0 g/cm^3) to derive a volumetric measure that is comparable with the NMR free-water and total water data. Based on borehole lithological information and core sample texture, every NMR data and core sample was assigned a hydraulic texture class. Mineralogical composition using XRD showed that quartz is the dominant mineral for fine, medium and gravely coarse sand. Mud contains up to 30 % montmorillonite and the remainder is kaolinite, whereas muddy sand contains ~10 % montmorillonite and quartz made up the remaining composition.

Comparison of the 2011 NMR data with the gravimetric water content indicated that the NMR survey could be underestimating downhole water content. Preliminary estimates of groundwater storage volumes which relied on the use of the 'free-water' data from the NMR survey in 2011 as a surrogate for effective porosity appear to be low. A systematic increase in the difference between gravimetric water and NMR total water with fining textures also suggests that the NMR instrument is not sensing a large portion of the hydroscopic moisture present in the clay. This has implications for using this tool for measuring total porosity and diffusion in clay aquitard. As magnetic susceptibility and ferruginous grain coating could not account for the systematic inconsistency, the mismatch between the NMR and gravimetric data may be due to either a calibration error in the NMR instrument, or the possibility of the instrument not fully detecting water in very small pore spaces. Comparison with a subset of the 2013 data which were recorded using the same echo spacing of 2.25 ms and processing parameters suggested a linear trend of ~20 vol. % lower free-water and total water in the 2011 data. Follow up discussion with Vista Clara indicates that the tool was repackaged into different housing without recalibration prior to the BHMAR logging program. A factor of 1.2 was applied to the 2011 water contents, assuming calibration is the sole error which resulted in a linear bias in all the processed data (Lawrie et al., 2012b).

In the matric potential experiments, the 25 Lexan-encapsulated cores sampled across the five hydraulic texture classes were fully saturated and weighed, and subsequently subjected to suction at 10 kPa, 70 kPa, and 200 kPa. The final stage was to allow the cores to dry in air, estimated at 10,000 kPa suction (Highnett, 2013). At each applied matric potential, the samples with the remaining water were weighed and the volumes of the shrunken cores measured. The total porosity was calculated using 1 – (bulk density / particle density). In a soil environment, water loss at 10 kPa and 70 kPa represents water held in the macro-pores that readily flows under gravity between saturation and field capacity. To determine the partial porosity at various matric potentials, the weight of water loss was determined by subtracting the total porosity by the volume of water still remaining in the core. The water retention curves for the sand show an inflexion point at 10 kPa, and suggest that water loss at this matric potential is representative of the effective porosity (Lawrie. et al., 2012b). No data was available for the mud samples at 10 kPa and 70 kPa matric potentials.

To determine the total porosity for each hydraulic texture class, statistical summaries of the NMR total water (2013 and recalibrated 2011 data) were compared against the water content at 200 kPa matric potential, total porosity from the matric experiment, and the volumetric gravimetric water from the oven drying method. NMR data from the unsaturated zone were excluded from the analysis.

Overall, the median total water of the 2013 and recalibrated 2011 data were either the same or very similar (±0.02 vol. ratio) across the five hydraulic texture classes (Table 2). The fractional water at 200 kPa matric potential relate closely to the total porosity for the coarse grained sediments. The small sample sizes ($n \leq 11$) of the matric experiment may result in a bias towards higher total porosity as compared to the NMR total water. The gravimetric water matched the NMR total water for fine (0.27 ±0.02 vol. ratio) and medium sand (0.29 ±0.02 vol. ratio), but was much lower for the gravely coarse sand due to water loss from the free-draining coarse sand during laboratory analysis. These results support that NMR total water are comparable to the total porosity for sand.

For fine textured sediment, the disparity in total water between the NMR data, matric potential and gravimetric water experiments (Table 2) indicates that the NMR tool is not measuring all of the total water. This is interpreted to be the impact of T_2 decays being less than the 1.5 ms and the low signal to noise in the fast decays. The total porosities from the matric experiment for mud and muddy sand are high (43 vol. % and 41 vol. % respectively) and probably represent the maximum porosities for montmorillonite-bearing mud-rich sediment, as the experiment allowed the cores to stand for 12 hours to fully saturate and swell. In contrast, in an in-situ environment where sediment was compressed by overburden, the gravimetric water of ~30 vol. % for mud and muddy sand is more likely.

Table 2. Median values of the total porosity (volume ratio) in each hydraulic texture class.

	200 kPa	**Total Porosity (Matric Potential)**	**2013 NMR Total Water**	**2011* NMR Total Water**	**Gravi-metric Water (oven dry)**
Gravely Coarse Sand	0.32 [0.09] (11)	0.31 [0.11] (11)	0.28 [0.07] (165)	0.28 [0.10] (469)	0.23 [0.06] (81)
Medium Sand	0.33 [0.09] (4)	0.36 [0.12] (4)	0.29 [0.07] (208)	0.29 [0.10] (739)	0.27 [0.04] (106)
Fine Sand	0.31 [0.02] (4)	0.38 [0.02] (4)	0.29 [0.09] (106)	0.31 [0.12] (401)	0.29 [0.04] (63)
Muddy Sand	0.29 [0.10] (3)	0.41 [0.07] (3)	0.23 [0.12] (196)	0.22 [0.14] (659)	0.29 [0.04] (66)
Mud	0.07 [0.08] (2)	0.43 [0.07] (2)	0.18 [0.13] (160)	0.19 [0.18] (539)	0.3 [0.03] (109)

Note: Values in bracket are inter-quartile range and values in parentheses show the number of measurements. * Recalibrated data.

Table 3. Median values of the effective porosity (volume ratio) in each hydraulic texture class.

	10 kPa	**70 kPa**	**2013 NMR Free-water**	**2011* NMR Free-water**
Gravely Coarse Sand	0.17 [0.14] (11)	0.22 [0.11] (11)	0.18 [0.11] (164)	0.16 [0.11] (469)
Medium Sand	0.20 [0.15] (4)	0.22 [0.14] (4)	0.18 [0.15] (208)	0.17 [0.12] (738)
Fine Sand	0.13 [0.06] (4)	0.16 [0.03] (4)	0.16 [0.16] (106)	0.16 [0.15] (409)
Muddy Sand	0.10 [0.20] (3)	0.10 [0.17] (3)	0.06 [0.11] (196)	0.05 [0.11] (659)
Mud	(0)	(0)	0.03 [0.04] (160)	0.02 [0.05] (539)

Note: Values in bracket are inter-quartile range and values in parentheses show the number of measurements. * Recalibrated data.

For NMR free-water, the median values of the 2013 data and recalibrated 2011 data are either the same or very similar (±0.01vol. ratio) across the five hydraulic texture classes (Table 3). The median NMR free-water contents are comparable, ±0.03 vol. ratio, to the matric potential results at 10 kPa and 70 kPa, which suggest the NMR data can be used as a surrogate for effective porosity for sand and gravely sand. There is an increase in disparity (±0.05 vol. ratio) between the matric potential results and NMR derived free-water for muddy sand. Considering the small number of samples (n = 3) and the fact that the cores were fully saturated at standard temperature and pressure as compared to in-situ environment, the water contents of the matric experiment may be overestimate. For mud, the NMR free-water indicates 0.02 vol. ratio to 0.03 vol. ratio (Table 3). However, without other independent supporting evidence, as the matric potential method could not be conducted on mud, these values should be treated with caution.

Apart from heterogeneity in sedimentary textures within the aquifer, the sediments also vary in the degree of sorting, evidenced from the disparity between the mean and mode of the grain size distribution (Lawrie et al., 2012b). The effective porosities, which rely on both the pore size and the connectivity of the pores, are readily affected by any heterogeneity in pore size distribution. The large inter-quartile range (≥ 0.11 vol. ratio, Table 3) in the free-water for the sands and muddy sand may have resulted from varied textural sorting.

The larger recalibrated 2011 data set is favoured over the 2013 data set in representing the effective porosities of the sediment. The lower and upper quartiles of the NMR free-water for each texture class were incorporated into the mapped litho-hydrostratigraphic model, which was derived from interpretation of: airborne electromagnetic data grids using WANDA inversion (Christensen, 2012); borehole induction and natural gamma logs; lithological information; stratigraphic; and hydrogeological models (Lawrie et.al., 2012b). The results derived from this investigation include the groundwater resource estimates for the individual target across the semi-confined aquifer.

CONCLUSIONS

A lower than expected effective porosity, derived from using the NMR free-water data collected in 2011, of the sand-rich sediment in the semi-confined aquifer prompted a series of follow-up investigations. These include examination of the NMR data processing parameters and the regularization factor, re-logging 10 bores using the improved inter-echo spacing and dual frequency Javelin system in 2013, conducting matric potential and gravimetric water experiments to determine the fractional water and total porosities, and a preliminary inquiry into the magnetic susceptibility and mineralogical composition of the sediments. It was concluded that a calibration error in the Javelin tool had caused the detection of lower water contents by 20 vol. %. A factor of 1.2 was applied to the processed 2011 data to rectify this issue. The laboratory experiments showed comparable results between the NMR free-water and total water contents for sand and muddy sand, but NMR underestimated the total water in mud. Having established that NMR free-water is a surrogate for effective porosity, the lower and upper quartiles of the NMR free-water (recalibrated 2011 data set) for each of the five hydraulic texture classes were used to derive the groundwater resource estimates in the semi-confined aquifer within the study area.

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