10.1071/PVv2017n186p29

Environmental geophysics

Mike Hatch
Associate Editor for
Environmental Geophysics
michael.hatch@adelaide.edu.au

Welcome readers to this issue's column on geophysics applied to the environment. I was having trouble coming up with interesting material for this issue (think about thinking about this over the Christmas holidays) and thought that I would try to crowd-source some ideas from some of my friends and acquaintances in the field of environmental geophysics – my thought was to write about some of the holy grails…

One of those holy grails is what to do in highly saline environments to identify aquifers and characterise them. Most of the signal in any electrical survey just doesn't penetrate very far into highly conductive ground, and the contrasts between where there is water that is easy to extract and where it isn't can be is very subtle. Well, Dave Walsh of Vista Clara has been doing some testing in some areas that are pretty saline and has been finding that NMR can do a great job of separating the aquifers from the aquitards and characterising hydrogeologic properties in these challenging environments. Here is Dave's story.

Identifying and characterising aquifers in saline environments

Dave Walsh
Vista Clara Inc.
davewalsh@vista-clara.com

Motivation for this work lies in the fact that the world's groundwater supplies are getting more and more stretched, and there is increased need for non-potable water for industrial and commercial use. Additionally, *in situ* mining operations, where mineral resources dissolved in saline groundwater are extracted through production wells, are increasingly common worldwide (Beverley and Honeymoon are both examples of *in situ* uranium mines in South Australia). Important mineral resources that are commonly extracted through *in situ* mining include uranium, gold, lithium, potash and copper. In areas where freshwater resources are scarce, such as in the China Lake basin in the southern California desert, water managers are increasingly investigating deeply sourced brackish groundwater as a potential resource for domestic and industrial water supplies (https://gemcenter.stanford.edu/research/aquifer-characterisation-indian-wells-valley-california-using-geophysical-techniques). In all of these settings (most of which are likely to be high in TDS) it is important to know the properties and location of the aquifers – which is hard to visualise using standard geophysical techniques.

Geophysical methods based on nuclear magnetic resonance (NMR) are being tested and used for saline aquifer investigations because they can provide direct and reliable estimates of key aquifer properties, including how much of the water at a given location is tied up in fine grained material (i.e. is bound) and how much of it is mobile, leading to the ability to make high quality estimates of hydraulic conductivity, even in cases where the groundwater is very electrically conductive. NMR logging tools have been successfully employed in highly conductive brine and petroleum reservoirs by the oil and gas industry for decades; this ability is now being extended to use in groundwater surveying.

When a NMR logging tool is immersed in an electrically conductive fluid and porous medium, the transmitted and received RF fields are affected via electromagnetic skin effects (as are inductive techniques), resulting in some reduction in field intensity. This reduction, if unaccounted for, can lead to underestimation of water content and porosity measurements. For example, Table 1 shows the NMR water content measured by a typical small diameter NMR logging tool (Javelin JP238, Vista Clara Inc.) in fresh, brackish and saline water. The results indicate that using a fresh water calibration, there are negligible effect on detected water content in brackish water with electrical resistivity of 0.5 ohm-m (2000 mS/m). A moderate

Table 1. Experimentally measured effects of electrically conductive water on the NMR-estimated water content of a Javelin JP238 NMR logging tool. Values are derived using fresh water calibration values

		Water content measured by NMR		
Operating frequency	**Diameter of cylindrical NMR sensitive shell**	**Fresh water (160 ohm-m)**	**Brackish water (0.5 ohm-m)**	**Saline water (0.1 ohm-m)**
432 kHz	21 cm	100%	96%	75%
365 kHz	23 cm	100%	98%	75%
305 kHz	26 cm	100%	100%	73%
248 kHz	30 cm	100%	100%	79%

effect on estimated water content is observed in saline water at 0.1 ohm-m (~10 000 mS/m) – remember that the ocean is about 0.2 ohm-m (5000 mS/m). NMR relaxation times, used to determine pore size and permeability are generally unaffected by the increase in salinity.

In practice, the effect of conductive water in earth formations is lower than suggested by Table 1, because the electrically conductive water fills only a fraction of the volume between the tool

accurate inversion of water content and other aquifer properties can be realised

and the NMR sensitive zone, so the bulk electrical conductivity is much lower than for the fluid alone (Archie's Law). No conductivity corrections are applied to the data in Table 1 and the accuracy in very conductive formations can be further improved if necessary using a calibration of the tool in a brine tank.

It is also well known that an electrically conductive earth affects the depth of investigation for surface NMR measurements. Again, as long as the electrical conductivity structure of the subsurface is known (via electrical resistivity or induction surveys), the effect of the electrically conductive earth on the magnetic field patterns can be accurately modeled and accurate inversion of water content and other aquifer properties can be realised (Weichman, 2000).

An example of the use of NMR geophysical measurements to characterise a saline aquifer system was demonstrated at a groundwater investigation site at Leque Island, in western Washington, USA. This site is an agricultural field that was previously reclaimed from marshland, adjacent to Puget Sound (an inland saltwater body). The upper 20 m of the subsurface consists of interbedded, unconsolidated sediments, varying from sand and gravel to silt and clay. Groundwater samples obtained from shallow monitoring wells at the site ranged from relatively fresh to brackish, with electrical conductivity measurements on groundwater samples ranging from 250 mS/m (4 ohm-m) to 2500 mS/m (0.4 ohm-m). Figure 1 shows a collocated direct push EC measurement (Figure 1a) and direct push NMR measurement using a JP238 NMR logging probe (Figure 1b–e). The NMR measurement (Figure 1b) and the NMR derived aquifer properties (Figure 1c–e) clearly indicate three distinct high permeability zones corresponding to well sorted sands and gravels, denoted as zones 1, 2 and 3. The NMR data in these zones were used to derive quantitative estimates of hydraulic conductivity that compared well to direct hydrologic measurements (Knight et al., 2016). In contrast, the direct push EC log (Figure 1a) shows much less correlation with aquifer properties and permeable zones. The EC log does clearly show that the groundwater transitions from relatively fresh above 5m, to relatively saline below 5 m.

In addition, 2D surface electrical resistivity (ERT) and 1D and 2D surface NMR data sets were collected along two parallel transects at this site. The ERT inversion, shown in Figure 2, (the direct push EC and NMR measurements shown in Figure 1 were collected on this transect), shows that this site is quite conductive, with some correlation between the slightly higher resistivities at the surface and the uppermost permeable layer between 3 m and 7 m (if you really squint at the section). The 2D surface NMR inversion (Figure 3), collected along a transect 100 m south of the ERT line, indicates a clear and laterally continuous aquifer zone between depths of 3 m and 7 m, and a lower, laterally discontinuous aquifer zone at a depth of about 15 m.

There is no question that there are shortages of drinkable water worldwide and that we need to make better use of the various qualities of groundwater that are available to us. NMR may offer a method to better characterise and delineate those groundwater resources that have been previously considered to be less than desirable and are also (therefore) hard to delineate.

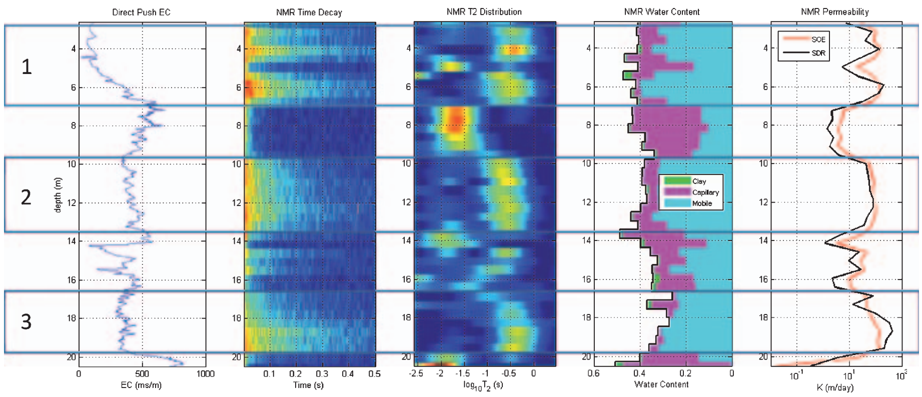

Figure 1. *Comparison of direct push electrical conductivity (a) and direct push NMR measured aquifer properties (b – e) at a site with brackish and saline groundwater, Leque Island Washington. The direct push EC log is dominated by the conductivity of the groundwater at this site, and hence provides little indication of the existence of the three high permeability zones. The direct push NMR log clearly indicates the presence and extent of three high permeability zones and provides quantified estimates of bound and mobile porosity and hydraulic conductivity.*

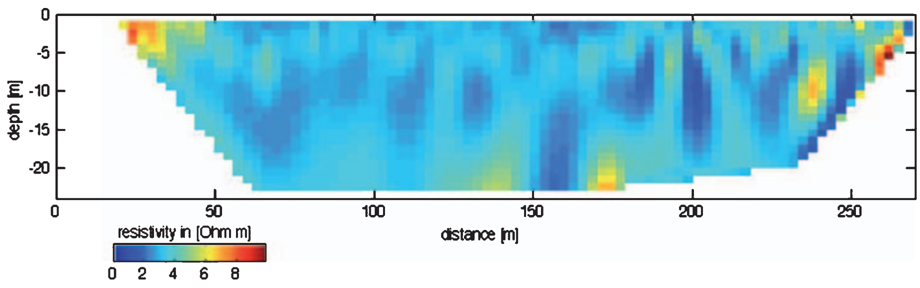

Figure 2. *2D electrical resistivity inversion, Leque Island Washington, USA, 2013. The electrical resistivity measurements are dominated by the conductivity of the groundwater below 5 m, and hence indicate little variability below 5 m.*

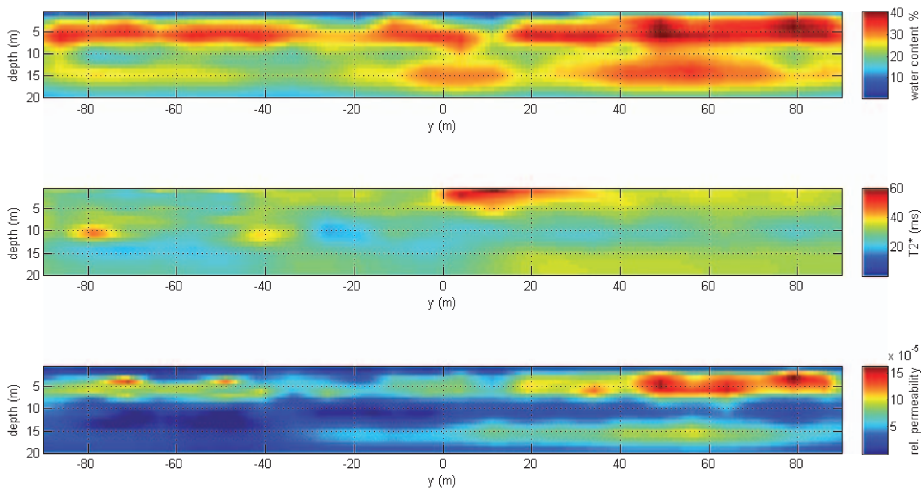

Figure 3. *2D surface NMR inversion, Leque Island Washington, USA, 2013. The 2D surface NMR inversion clearly indicates the presence of a laterally continuous upper aquifer at a depth of about 5 m, and a laterally discontinuous aquifer at a depth of about 15 m.*

References

Knight, R., Walsh, D. O., Butler, Jr., J. J., Grunewald, E., Liu, G., Parsekian, A. D., Reboulet, E. C., Knobbe, S., and Barrows, M., 2016, NMR Logging to estimate hydraulic conductivity in unconsolidated aquifers: *Groundwater*, **54**(1), 104–114. doi:10.1111/gwat.12324

Weichman, P. B., Lavely, E. M., and Ritzwoller, M. H., 2000, Theory of surface nuclear magnetic resonance with applications to geophysical imaging problems: *Physical Review E*, **62**(1), 1290.