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Nuclear Magnetic Resonance (NMR) Logging - Lessons Learned at the USGS Cape Cod Toxic Substances Hydrology Research Site, Massachusetts

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SUMMARY

Over the last 30 years, advancements have been made in developing borehole geophysical tools and methods for determining aquifer hydraulic properties that control solute transport. More recent advances in technology allow for nuclear magnetic resonance (NMR) logging of small-diameter boreholes typical of environmental studies. Advantages of the NMR logging method are that (1) NMR does not use active nuclear sources to determine water content, and (2) NMR provides depth-dependent estimates of pore-size distribution that allow for the distinction between bound- and mobile-water fractions, which is not possible with active-source logs.

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NMR logging, flowmeter logging, and hydraulic testing have been conducted at the U.S. Geological Survey Toxic Substances Hydrology Research Site on Cape Cod, Massachusetts to estimate aquifer properties and evaluate the performance of the slim-hole NMR tools. Between 2010 and 2013, NMR measurements were conducted in eight boreholes located in the USGS research site and in a ninth borehole located on the adjacent Joint Base Cape Cod (JBCC) military reservation. The nine boreholes range in diameter from 5.1 to 10.2 cm and in depth from 24 to 98 m below land surface. The aquifer sediments in the research site are medium to coarse grained glacial outwash sand and gravel. The aquifer sediments at the JBCC borehole were similar, but have some interbedded silt and fine sand. Each NMR measurement provided estimates of total water content, bound- and mobile-fraction of water over depth intervals as small as 0.5 m and radially from 10 to 19 cm from the center of the borehole, depending on the NMR probe that was used. Estimates of permeability were computed using these water-content estimates and the parameters of the measured relaxation time (T2 distribution). The NMR-derived total-water content estimated in the research-site boreholes compare well to historical active-source logs and to the effective porosity determined from hydraulic and solute-transport tests at the site. The NMR estimates of hydraulic conductivity correlated with flowmeter and hydraulic tests from the site. In the JBCC borehole, similar correlations were found between the NMR and active-source total-water estimates. The zones of bound water correlated with the location of layers of silt and fine-grained sand that were identified in the electromagnetic induction (EMI), gamma, and lithologic logs. In general, NMR has facilitated obtaining depth-dependent water content and permeability estimates that are consistent with previously determined results at the site.

Improved field techniques for NMR data-collection and data-processing methods learned through this multi-year logging effort include: NMR operators should (1) log in a downward direction to avoid or minimize accumulation of metallic debris on the tool magnets that adversely affect measurements; (2) avoid pumping in nearby wells as the motion of water can violate the assumption that water molecules reside within a single pore during the measurement; (3) avoid electromagnetic interference that cause noise in the data by temporarily turning off local data-telemetry systems and pumps; (4) remove noise with de-spiking, phase-matching, and noise-removal processes when necessary; and (5) at a minimum collect EMI, gamma and magnetic susceptibility or magnetic-field strength logs to help compare and interpret the NMR response.