Nuclear Magnetic Resonance Logging of a Deep Test Well for Estimation of Aquifer and Confining-Unit Hydraulic Properties, Long Island, New York

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Abstract

A 1,200-foot deep well in southwestern Nassau County, Long Island, N.Y. was selected to evaluate the application of a nuclear magnetic resonance (NMR) logging tool. Technological advances in NMR borehole systems have allowed for reduced probe length and diameter, and focused measurement at specific diameters beyond the disturbed zone surrounding a well. This 3-inch-diameter NMR tool was specifically developed for use in deep 4-inch-diameter polyvinyl chloride cased wells common to Long Island. Selected intervals of the Magothy and Lloyd aquifers and the Raritan confining unit were logged for the evaluation.

Unlike other petrophysical logs that respond to the rock matrix and fluid properties and are strongly dependent on mineralogy, NMR logs respond to the presence of hydrogen protons in the formation fluid to determine water fraction and pore-size distribution. NMR log analysis provided estimates of the clay-bound, capillary-bound, and mobile water fraction and hydraulic conductivity of aquifers and confining units penetrated by the well. NMR-estimated porosity and mobile water fraction for the Magothy aquifer (0.34 and 0.22 respectively), Magothy/Raritan(?) sand (0.35 and 0.30), Raritan confining unit (0.30 and 0.13), Raritan clay- and silt-rich lower part (0.23 and 0.01), and the Lloyd aquifer (0.27 and 0.19) was determined from the NMR log.

Hydraulic conductivity was estimated from the NMR-log data using the Schlumberger-Doll Research and sum of squared echoes equations with empirically derived constants for unconsolidated aquifers. Average hydraulic conductivity of the Magothy aquifer was 70 ft/d, the Raritan confining unit was 9.0 ft/d overall, the clay and silt-rich lower part was 0.24 ft/d, and the Lloyd aquifer was 56 ft/d. The sandy Magothy/Raritan(?) unit (not yet defined as a distinct unit) between the Magothy aquifer and the top of the Raritan confining unit had the highest hydraulic conductivity of 345 ft/d. The hydraulic-conductivity estimates from the NMR log analysis for the Magothy and Lloyd aquifers were consistent with published values and with the values estimated for the Lloyd aquifer from a specific-capacity test at the well site.

Introduction

In 2016, the U.S. Geological Survey (USGS) began a cooperative study with the New York State Department of Environmental Conservation (NYSDEC) to evaluate the sustainability of Long Island's sole-source aquifer system through hydrogeologic mapping, monitoring of groundwater quality and levels, and construction of a groundwater-flow model. As part of the Long Island Groundwater Sustainability study, a newly developed nuclear magnetic resonance (NMR) logging tool was compared with conventional aquifer parameter estimation methods at a deep test-well on Long Island (fig. 1).

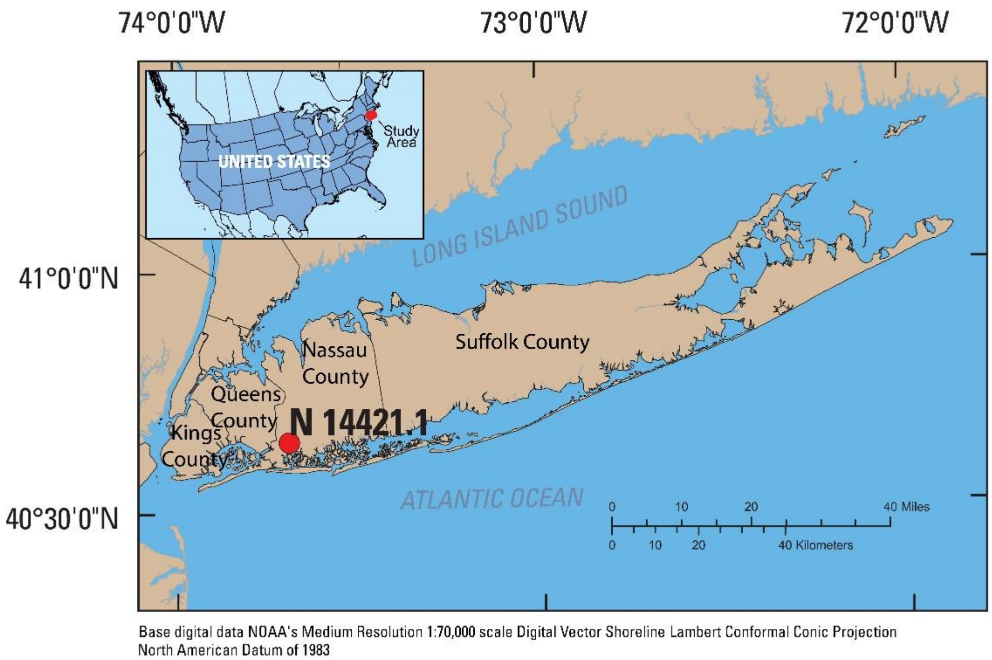

Figure 1. Location of deep test well N 14421.1 in southwestern Nassau County, Long Island, New York.

Hydrogeologic Setting and Well Description

Long Island is underlain by unconsolidated glacial deposits of Pleistocene age and coastal-plain deposits of Late Cretaceous age (Fuller, 1914; Suter and others, 1949) (fig. 2). These deposits consist of gravel, sand, silt, and clay and rest upon a southeastern sloping bedrock surface of Paleozoic age (Baskerville, 1994; Merguerian and Baskerville, 1987). The hydrogeologic framework of Long Island is presented in Smolensky and others (1989).

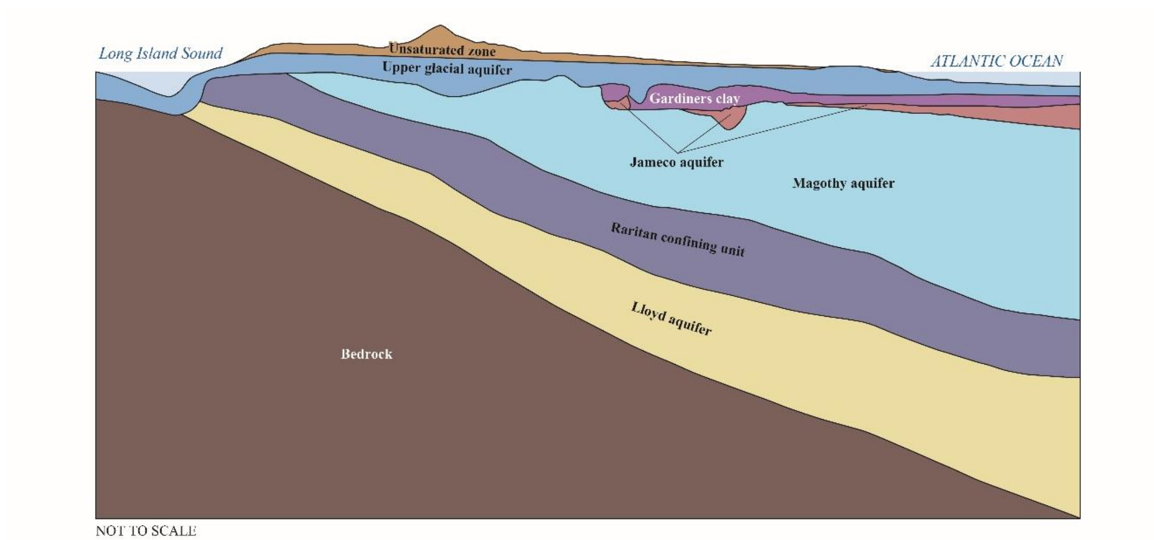

Figure 2. Generalized cross section of the major hydrogeologic units underlying Long Island, N.Y. (Modified from Stumm and others, 2020)

Well N 14421.1 (USGS site ID 403844073412701), located in southwestern Nassau County, N.Y (fig. 1), was drilled through glacial deposits and the entire Cretaceous coastal-plain sequence to bedrock at a depth of 1,200 feet below land surface (ft bls) by the mud-rotary method with a 9.6-inch bit. Steel surface casing was set to a depth of 40 ft bls. Split-spoon core samples were collected at 20-ft intervals during drilling. The well was completed with 4-inch diameter Schedule 80 polyvinyl chloride (PVC) casing with enhanced couplings to prevent casing leakage and screened from 1,130 to 1,150 ft bls.

Natural-gamma radiation (gamma), spontaneous potential (SP), single-point-resistance (SPR), short- and long-normal resistivity (R), and focused electromagnetic-induction conductivity (EM) logs were collected in the mud-filled open borehole prior to installation of PVC casing. Gamma, electric, and electromagnetic logs were analyzed along with core samples to define aquifer and confining unit contacts and thicknesses (Keys, 1990; Williams and others, 1988) (fig. 3). The geophysical and lithologic logs of the well are available from the USGS GeoLog Locator (U.S. Geological Survey, 2022a). The Cretaceous aquifers and confining unit penetrated at the well site are described in the following sections.

Magothy Aquifer

The Magothy aquifer extends throughout most of Long Island. In Nassau, Queens, and Kings Counties, it lies unconformably beneath the upper glacial aquifer in the northern and central areas and Gardiners clay on the southern shore (Suter and others, 1949; Smolensky and others, 1989). The Magothy aquifer deposits are an upward fining sequence of alternating beds of sand, silt, and clay with gravel common in the basal zone. The well penetrated the top of the Magothy aquifer at about 50 ft bls and the bottom at about 605 ft bls (fig. 3). This unit is about 555 ft thick at the well site.

Magothy/Raritan(?) Sand

The sandy sequence below the basal gravel of the Magothy aquifer and above the clay and silt of the Raritan confining unit is currently being investigated as part of the Long Island Groundwater Sustainability study through analysis of hundreds of core samples and geophysical logs to determine if this sequence merits broad scale definition as a distinct unit. In this paper, the sandy sequence penetrated by the well from 605 to 650 ft bls (fig 3) is referred to as the Magothy/Raritan(?) sand.

Raritan Confining Unit

The Raritan confining unit overlies and confines the Lloyd aquifer (Suter and others, 1949; Stumm, 2001). The Raritan confining unit penetrated by the well consists of upward-coarsening sequences of silt and sand with some clay from 650 to 750 ft bls and dense clay and silt from 750 to 786 ft bls (fig. 3). This unit is about 136 ft thick at the well site.

Lloyd Aquifer

The Lloyd aquifer lies conformably beneath and is confined by the Raritan clay (Suter and others, 1949). The Lloyd aquifer rests unconformably on bedrock throughout most of Long Island and is up to 400 ft thick. The Lloyd aquifer consists of an upward fining sequence of fine to coarse sand and gravel with lenses of silty clay. The well penetrated the top of the Lloyd aquifer at about 786 ft bls. This unit is about 370 ft thick at the well site.

Specific-Capacity Test

A specific-capacity test was conducted on well N 14421.1 on December 13, 2019. The well was pumped at 37.5 gallons per minute (gal/min) for 1.4 hrs. The initial water level was at 9.69 ft bls, and the quasi-steady-state pumping water level was at 16.35 ft bls for a calculated drawdown of 6.66 ft and specific capacity of 5.6 gallons per minute per foot (gal/min/ft). The Lloyd aquifer is about 370 ft thick at the well, with the screen zone partially penetrating the aquifer from 1,130 to 1,150 ft bls. Hydraulic conductivity was estimated from the specific-capacity test, well-construction, and aquifer information following the method of Bradbury and Rothschild (1985). The method applies the Cooper-Jacob approximation

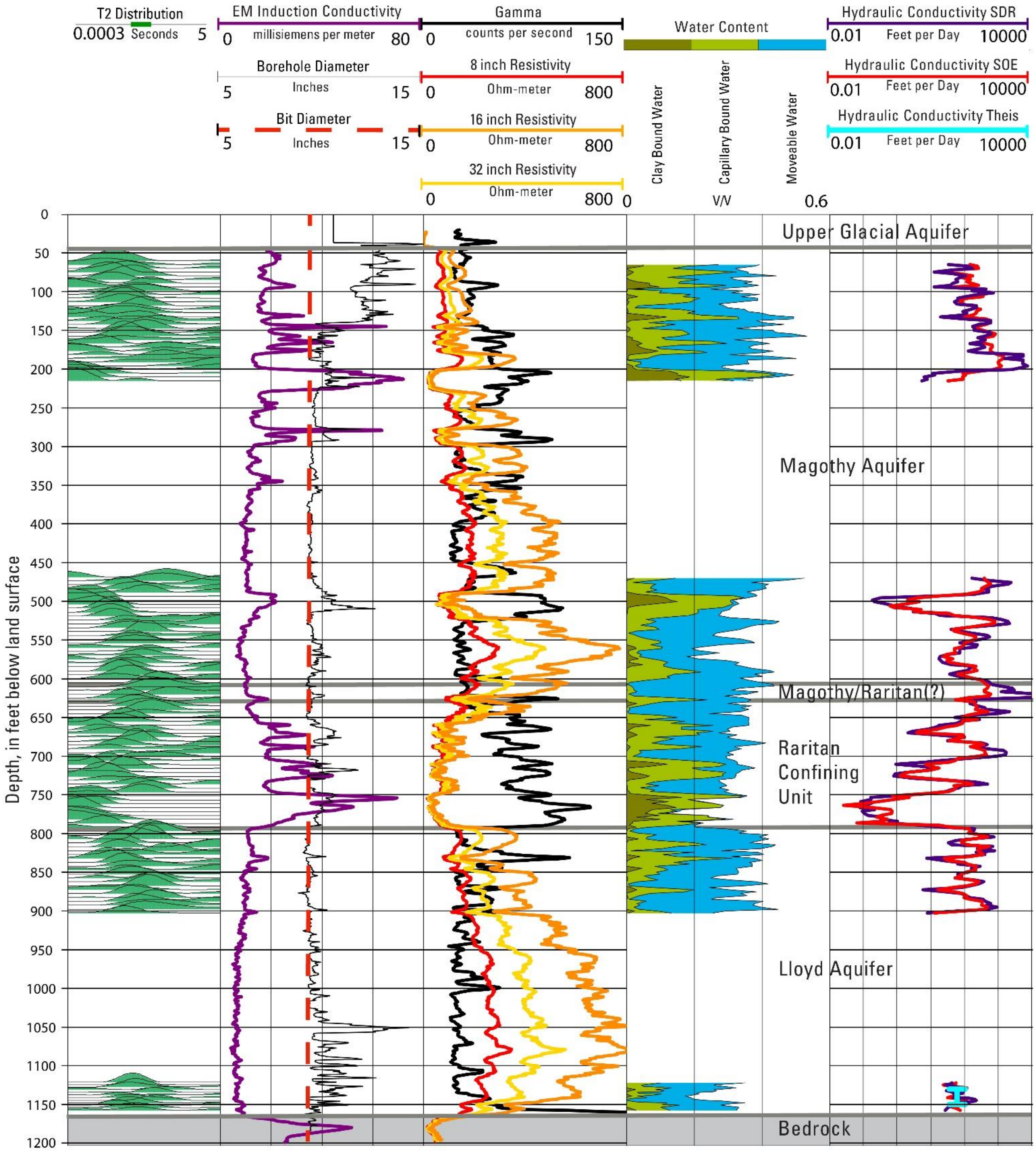

Figure 3. A suite of borehole geophysical logs collected at well N 14421.1 including gamma, electromagnetic-induction conductivity (EM), electric, induction, caliper, and nuclear magnetic resonance (NMR) logs. (Location shown in figure 1). The Magothy/Raritan (?) sequence is currently being investigated to determine if it merits broad scale definition as a distinct unit.

of the Theis (1935) equation. The method assumes that the tested aquifer is confined, nonleaky, homogeneous, and isotropic; flow is radial to the pumping well; well loss is known; aquifer thickness is known; and the storage coefficient of the aquifer is known. The correction factor of Brons and Marting (1961) was used to account for partial penetration of the well, well loss was assumed to be negligible, and the confined storage coefficient was assumed to be 1 x 10^{-5}. The results of the specific-capacity test are stored in the USGS National Water Information System database and available through the USGS Aquifer Test Locator (U.S. Geological Survey, 2022b). The estimated horizontal hydraulic conductivity estimated from the specific-capacity analysis was 47 feet per day (ft/d).

Nuclear Magnetic Resonance Logging Method

Atoms with an odd number of protons or neutrons possess a magnetic moment and a nuclear spin angular momentum, allowing them to absorb and transmit energy when disturbed from equilibrium (Bloch,1946; Purcell and others, 1946). In the NMR logging method, an antenna within the logging tool transmits electromagnetic energy at pre-selected frequencies in precisely timed pulses causing the hydrogen protons to be perturbed. Between the pulses of energy, the antenna measures the decaying echo signal from the hydrogen protons in the surrounding geologic materials as they resonate (Coates and others, 1999) (fig. 4). After perturbation, the spins return, or “relax,” to their initial state (Dlubac and others, 2013). The relaxation is quantified as a time constant: the time associated with the decay of the magnetization in the direction perpendicular to the background field. Due to a linear relation between the proton resonance frequency, and the strength of the permanent magnetic field, the frequency of the transmitted and received energy are tuned to measure narrow cylindrical areas at different diameters from the tool (Coates and others, 1999). The time between each pulse is referred to as the echo time. The recorded spin-echoes between each pulse have amplitudes that decay over time, which are fit with a multi-exponential curve representing the T2 relaxation time (Crow and others, 2020).

The NMR tool operates at two independent frequencies to measure magnetic resonance at two different radii of investigation (ROI). The higher frequency shell (F1) operates at about 350 kilohertz (kHz) and has a ROI of about 12.5 inches, and the lower frequency shell (F2) operates at about 250 kHz and has a ROI of about 14.5 inches. The vertical resolution of the probe measurement is 1.23 ft (0.375 m). Low signal-to-noise ratios require the NMR tool to be logged at a speed of 1.5 ft per minute.

Nuclear Magnetic Resonance Log Estimation of Hydraulic Properties

Unlike other petrophysical logs that respond to the rock matrix and fluid properties and are strongly dependent on mineralogy, NMR logs respond to the presence of hydrogen protons in the formation fluid to determine water content (equivalent to porosity in the saturated zone) and pore-size distribution (bound versus mobile water). Processed NMR tool data can provide information about the geologic materials surrounding a PVC-cased well. This information includes the porosity of the water-filled sediment analyzed to determine mobile, capillary-bound, and clay-bound water fraction and estimate hydraulic conductivity (fig. 5). The Schlumberger-Doll Research (SDR) and the Timur-Coates (T-C) equations are commonly used to obtain estimates of permeability from NMR-derived logs in the petroleum industry (Seevers, 1966; Timur, 1969; Kenyon et al., 1988; Coates and others, 1999); both equations require empirically determined constants. The SDR equation and a third equation, sum of squared echoes (SOE), which also requires empirically determined constants, have been used for unconsolidated sediments (Walsh and others, 2013; Knight and others, 2010; Kendrick and others, 2021).

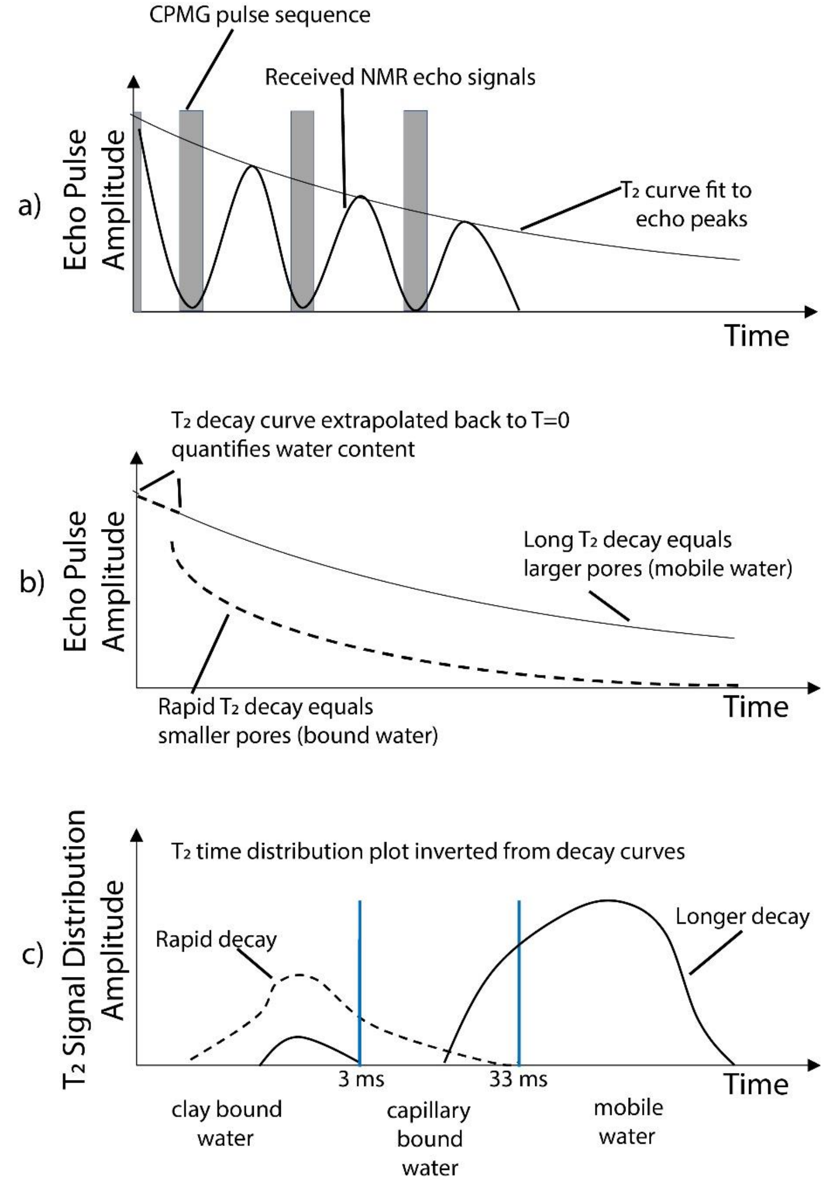

Figure 4. (a) A sequence of nuclear magnetic resonance (NMR) measurements includes radio-frequency magnetic pulses transmitted by the tool antenna and the relaxation rate of the hydrogen protons in the groundwater fit with a multi-exponential decay curve (T2). (b) The shape of the T2 decay is controlled by the amount of the water in the formation and its distribution in the pores. (c) An amplitude–T2 distribution plot, obtained by an inversion of the decay curves shown in (b), reflects pore-size distributions in the sediments. Carr-Purcell-Meiboom-Gill pulse train (CPMG).

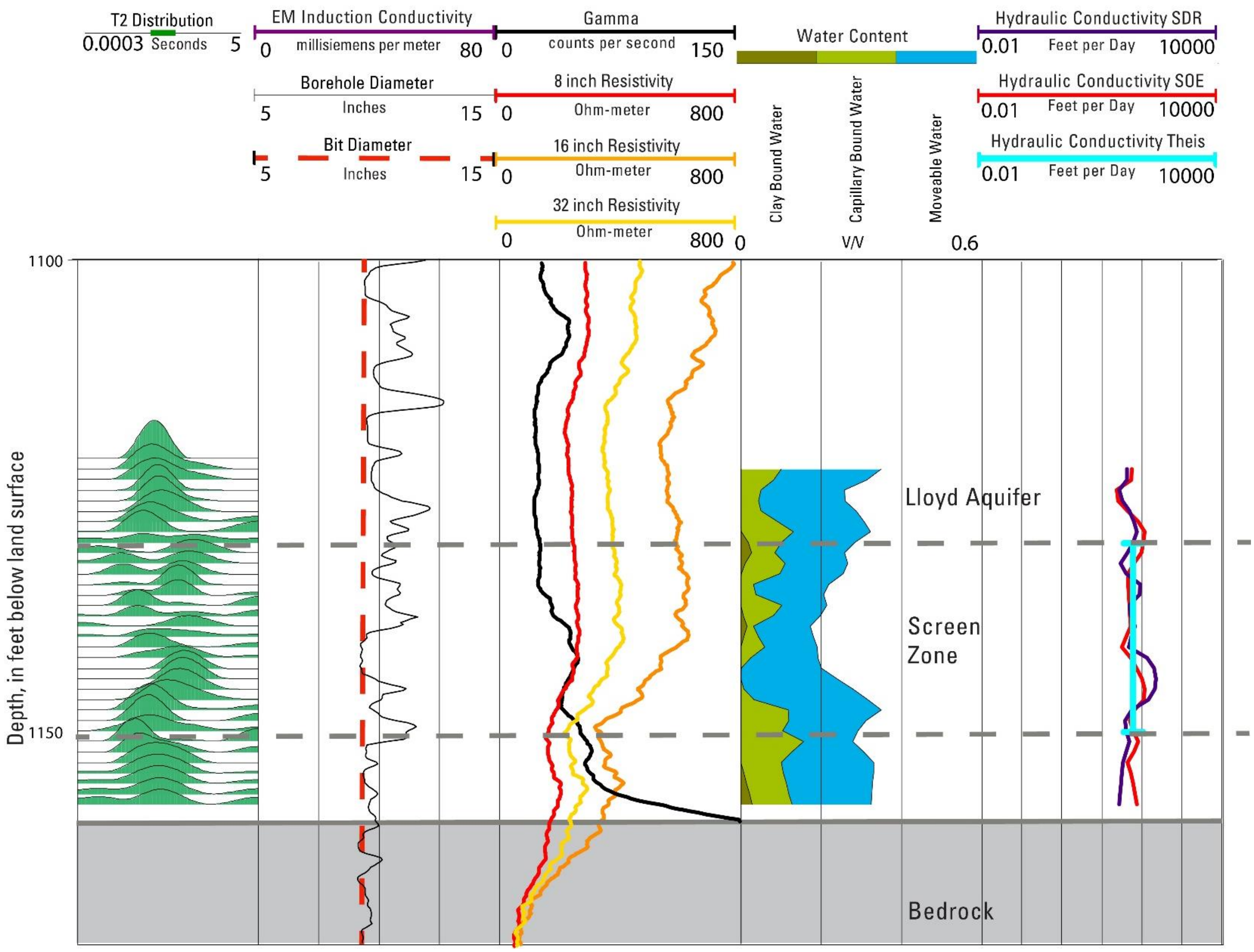

Figure 5. Expanded view of the lower part of figure 3 and the borehole geophysical log suite collected at N 14421.1 (Location shown in figure 1). Theis hydraulic conductivity was estimated from a specific capacity test. The Schlumberger-Doll Research (SDR) and sum of squared echoes (SOE) hydraulic conductivities were estimated from the Nuclear Magnetic Resonance (NMR) log.

Horizontal hydraulic conductivity was estimated from the NMR log T_2 measurements using the SDR and SOE equations. The SDR equation for estimation of horizontal hydraulic conductivity is:

$$\boldsymbol{k = C_{SDR}\phi_{NMR}^{a}T_{2ml}^{b}}$$

where f_{NMR} is the NMR-derived porosity, T_{2ml} is the logarithmic mean of the T_2 distribution, and C_{SDR}, *a*, and *b* are empirically derived constants equal to 8,900, 2, and 1, respectively.

The SOE equation estimates hydraulic conductivity as a function of the squared echo decay curve:

$$\boldsymbol{k = C_{SOE}\int S(t)^2 dt}$$

where C_{SOE} is an empirically derived constant equal to 4,200, and *S(t)* describes the echo decay curve. The constants C_{SDR}, *a*, *b*, and C_{SOE} are based on a compilation of regressions determined from published co-located hydraulic tests of unconsolidated aquifers (Walsh and others, 2013; Knight and others, 2010; and Kendrick and others, 2021).

Nuclear Magnetic Resonance Log Collection and Analysis of the Deep Well

The NMR logging system used to log well N 14421.1 consists of the downhole tool, drawworks, and surface control unit. The logging tool is 3 inches (76 mm) in diameter, and about 10 ft in length. The tool consists of two sections, the lower probe, and an upper digital power module, that are assembled onsite using integrated field joints. The tool connects to a drawworks with 2,300 ft (700 m) of 4-conductor wireline allowing for logging of deep 4-inch diameter PVC cased wells. The surface unit contains depth and power controls, electronics, and telemetry.

The NMR tool operates at two independent frequencies to measure magnetic resonance at two different radii of investigation (ROI). The higher frequency shell (F1) operates at about 350 kilohertz (kHz) and has a ROI of about 12.5 inches, and the lower frequency shell (F2) operates at about 250 kHz and has a ROI of about 14.5 inches. The NMR tool was logged at a speed of 1.5 ft per minute to obtain a vertical resolution of 1.23 ft.

Well N 14421.1 was logged with the NMR system on December 2, 2021. Three depth intervals were used to evaluate the NMR system: 1) upper Magothy section where anthropogenic radio noise levels were expected to be highest; 2) lower Magothy-Raritan-upper Lloyd section where the range of clay-bound, capillary-bound, and mobile water fractions was expected to be the greatest; and 3) the lower Lloyd section that was screened where an estimated hydraulic conductivity from the specific-capacity test was available to compare with that estimated from the NMR log.

Electromagnetic frequencies used by local radio stations can cause interference in the signals collected by the NMR tool especially in the upper 200 ft below the land surface. Fast down logging indicated that the F2 noise levels were excellent (less than 10 percent) from 55 ft (started logging 10 ft below steel surface casing) to total depth. F1 noise levels were slightly less than those of F2 below 400 ft but increased to unacceptable levels above 200 ft due to anthropogenic radio interference. The F1 water-fraction data generally tracked that of the F2 where noise levels for both were below 10 percent. However, the F1 and F2 data did differ and, in one case, the F1 data indicated an anomalous thick interval of capillary-bound water most likely because the ROI was within the disturbed formation in a washout zone. Therefore, only the F2 data were used to determine the water fractions and estimate hydraulic conductivity for the well site.

The average NMR estimated porosity for the lower Magothy aquifer section (470 to 605 ft bls) was 0.34 with a mobile water fraction of 0.22 (fig. 3). The average horizontal hydraulic conductivity of this Magothy aquifer section estimated using the SDR and SOE equations was 70 and 72 ft/d, respectively (average of 71 ft/d). The NMR-log derived hydraulic-conductivity estimates are consistent with published values for the Magothy aquifer of 50 to 70 ft/d (McClymonds and Franke, 1972).

The average NMR estimated porosity of the Magothy/Raritan(?) sand (605 to 650 ft bls) was 0.35 with a mobile water fraction averaging 0.30 (fig 3). The average horizontal hydraulic conductivity of the unit estimated using the SDR and SOE equations was 450 and 240 ft/d, respectively (average of 345 ft/d) (fig. 3).

The average NMR estimated porosity of the Raritan confining unit (650 to 786 ft bls) was 0.30 with an average clay- and capillary-bound water fraction of 0.09, and mobile water fraction of 0.13 (fig. 3). The average horizontal hydraulic conductivity of the Raritan confining unit using the SDR and SOE equations was 8 and 10 ft/day, respectively (average 9 ft/d). In contrast, the Raritan dense clay and silt from 750 to 786 ft bls had an estimated average porosity of 0.23 and a clay-bound water fraction of 0.08, capillary-bound water fraction of 0.14, and mobile water fraction of 0.01. The average horizontal hydraulic conductivity of the Raritan dense clay and silt using the SDR and SOE equations was 0.19 and 0.29 ft/day, respectively (average 0.24 ft/d).

Using the SDR and SOE equations the estimated horizontal hydraulic conductivity of the part of the Lloyd aquifer logged from 1,120 to 1,157 ft bls was 54 and 57 ft/d, respectively (average of 56 ft/d) (figs. 3 and 5). The NMR-log derived hydraulic-conductivity estimates are consistent with published values for the Lloyd aquifer of about 50 ft/d (McClymonds and Franke, 1972) and the value of 47 ft/d estimated from analysis of the specific capacity test at the well site. Estimated porosity over the interval logged averaged 0.27 with a mobile water fraction averaging 0.19.

The good agreement between the hydraulic-test derived hydraulic conductivity and that derived from the SDR and SOE equations suggests NMR logging of PVC-cased wells is a viable tool for high-resolution vertical mapping of hydraulic conductivity of Long Island aquifers. NMR logging of additional wells and comparison with hydraulic-test results will help to corroborate this finding and refine the SDR and SOE equation constants.

Summary and Conclusions

In 2016, the U.S. Geological Survey (USGS) began a cooperative study with the New York State Department of Environmental Conservation (NYSDEC) to evaluate the sustainability of Long Island's sole-source aquifer system through hydrogeologic mapping, monitoring of groundwater quality and levels, and construction of a groundwater-flow model. As part of the Long Island Groundwater Sustainability study, a newly developed nuclear magnetic resonance (NMR) logging tool was compared with conventional measures of aquifer parameters at a deep test-well site on Long Island.

Well N 14421.1 was drilled through glacial deposits and the entire Cretaceous coastal-plain sequence to bedrock at a depth of 1,200 feet below land surface (ft bls) by the mud-rotary drilling method with a 9.6-inch bit. A suite of borehole geophysical logs was collected in the mud-filled, open borehole, prior to installation of PVC casing and screen. Gamma, electric, and electromagnetic logs were analyzed along with core samples to define aquifer and confining unit contacts and thicknesses. Hydraulic testing of the Lloyd aquifer screen zone indicated a specific capacity of 5.6 gal/min/ft and a horizontal hydraulic conductivity of 47 ft/d.

The NMR tool can provide the water-filled porosity of the sediment analyzed to determine free, capillary-bound, and clay-bound water fraction and estimate hydraulic conductivity. NMR logging provides advantages over traditional aquifer pumping tests in that the estimated hydraulic conductivity is nearly continuous throughout the length of a PVC cased well and includes clay and silt units along with all aquifers penetrated by the well, compared to aquifer tests which are restricted to the screen zone.

The NMR data indicated good correlation to published hydraulic conductivities of the Magothy and Lloyd aquifers. The hydraulic conductivity value calculated from the specific capacity test data for the Lloyd screen zone was nearly identical to that estimated from the NMR tool. The Raritan confining unit has limited hydraulic testing data so further analysis is needed to assess the NMR tool's effectiveness in this unit.

The NMR derived average hydraulic conductivity of the Magothy aquifer was 71 ft/d, the Raritan confining unit was 9 ft/d overall with the clay- and silt-rich lower part 0.24 ft/d, and the Lloyd aquifer was 56 ft/d. The sandy unit between the Magothy aquifer and the top of the Raritan confining unit had the highest hydraulic conductivity of 345 ft/d. This hydrogeologic unit is currently being studied as part of the ongoing Long Island Groundwater Sustainability study.

The NMR derived porosity and water fraction indicates the Raritan confining unit consists of sandy and silty parts with significantly higher hydraulic conductivity at this location than estimated in the literature. The lower part is dominated by clay that consists of more silt than previously described.

The good agreement of the horizontal hydraulic conductivity from hydraulic tests and that estimated from the NMR logging data indicates the current equations applied to the NMR data are applicable. Further calibration of this new geophysical tool for application to Long Island's glacial and coastal plain hydrogeologic units using hydraulic-test data is ongoing at other observation wells.

Acknowledgements

The authors would like to thank Andrew Lange, Marie Zuck, and Michael Como of the USGS New York Water Science Center for their extensive field work collecting aquifer test data, core samples, water-quality samples, and assistance in collecting the borehole geophysical logs during drilling of this and other wells. Thanks are extended to Carole Johnson of the USGS Hydrogeophysics Branch of the Earth System Processes Division for her helpful advice and guidance on field testing the tool. The authors also thank Delta Well and Pump Co., Inc. for drilling the well and collecting the core samples. We also thank the Nassau County Department of Parks, Recreation, and Museums for providing access to their park. This research was funded in part by the New York State Department of Environmental Conservation as part of the Long Island Groundwater Sustainability study.

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