Applications of Advanced Borehole Geophysics to Groundwater Resources Management

Robert G. Maliva*
Schlumberger Water Services, 1567 Hayley Lane, Suite 202, Fort Myers, FL 33907, USA
RMaliva@slb.com

and

Thomas M. Missimer
Schlumberger Water Services, 1567 Hayley Lane, Suite 202, Fort Myers, FL 33907, USA

Summary

Groundwater resources management has become more complex as fresh groundwater resources are increasingly under threat from over-pumping and contamination, and alternative supplies need to be developed. More detailed aquifer characterization and modeling are required for the optimization of the use and protection of groundwater resources. Advanced borehole geophysical logging techniques developed for the oil and gas industry allow for borehole wall imaging, identification of mineral phases, improved quantification of porosity (total and pore size distribution), and measurement of hydraulic conductivity. Such techniques can provide important information as part of aquifer characterizations that might not be otherwise practicably obtainable and may be a cost-effective alternative to some commonly used testing procedures.

Introduction

Water has been described as "the defining crises of the twenty-first century" (Pearce, 2006). In many areas of the world, use of fresh groundwater resources is at or exceeds sustainable levels. Much effort is now being focused on the optimization of the use of existing water resources and the development of new, alternative water sources, such as desalination of brackish groundwater or seawater. Historically, water development did not require a high degree of technical sophistication, because water was readily available and easy to obtain. However, the performance of alternative water supply and management systems are much more sensitive to local hydrogeologic conditions. Aquifer characterization thus has increasing importance in groundwater resources management and development.

Borehole geophysical logging has long been a fundamental technology in the oil and gas industry and is widely used in water-resources investigations. However, the logging technology typically used in groundwater investigation is literally decades behind that employed in the oil and gas industry. The main reasons for the technology gap lie in that advanced technology historically was not needed for groundwater development and the low monetary value of water precluded use of advanced technologies for economic reasons irrespective of their benefits (Maliva et al., 2009). The groundwater modeling performed for most investigations has also not been sophisticated or detailed enough to incorporate the fine-scale data that can be provided by advanced geophysical technologies.

Information Needs for Alternative Water Supply Projects

Investigations of conventional freshwater resources have usually focused largely on aquifer drawdowns and their associated impacts. Solute-transport may also be an important concern where production occurs near groundwater of lesser quality, such as near saline-water/freshwater interfaces. Solute-transport tends to be a much greater concern in many alternative water supply projects and related injection well systems. Alternative water-supply system assessment, design, and operational performance depend to a large degree upon the flow patterns of produced and injected water. It is necessary to know from where produced water is being derived and where injected water will flow within an aquifer system.

Reverse-osmosis (RO) desalination systems are designed to treat water with a composition falling within a defined envelope. Membranes and high-pressure pump systems are designed to treat water within a specified salinity range. In order to design an RO desalination system that may have an operational life of 20 years or more, it is necessary to know both current water chemistry and how the composition of the water may evolve over the operational life of the system. A critical technical issue for the development of a brackish-water RO facility is predicting, through groundwater modeling, the magnitude of the salinity change and other significant water-quality changes over time. Principal concerns are vertical migration of saline water (up-coning) and horizontal migration of more saline waters. Data needed for model development include aquifer and confining zone hydraulic properties, the spatial distribution of salinity, and the degree and type of aquifer heterogeneity.

Aquifer storage and recovery (ASR) and other managed aquifer recharge (MAR) projects involve the storage (or replenishment) of water within aquifers. Depending upon the system type, the actual injected water may have to be recovered (Maliva and Missimer, 2008). System performance, as measured by recovery efficiency, is dependent upon the degree of movement and mixing of injected water and native groundwater, which is affected by aquifer heterogeneity (Maliva et al., 2006, 2009). Fluid-rock interactions can adversely impact the quality of stored water. In addition to basic aquifer hydraulic data (transmissivity, storativity, leakance), additional data are needed for system assessment and model development on (1) the abundance and distribution of reactive minerals, (2) degree of aquifer heterogeneity and location of flow zones, (3) type of porosity and permeability (single versus dual-porosity), (4) effective porosity, and (5) dispersivity (Maliva et al., 2009).

Deep injection well systems are widely used for the disposal of liquid wastes, including concentrate from desalination facilities, industrial wastes, and waters produced during oil and gas production. Critical issues in the design and operation of injection well systems is the location of strata that are sufficiently transmissive to accept the waste flows and have adequate confinement to prevent migration of the injected wastes into groundwater resources that are actual or potential water supplies. Data are needed on the hydraulic properties of potential injection and confining strata and on whether or not fractures or other secondary porosity features are present that can result in enhanced vertical or horizontal flow.

Advanced Borehole Geophysical Logging Technologies

The applications of borehole geophysical logging to groundwater investigation were reviewed by Driscoll (1986), Keys (989, 1990, 1997), and Kobr et al. (2005). The standard geophysical logs run for groundwater resources investigations include the following: caliper, natural gamma ray, spontaneous potential, resistivity (lateral and dual-induction), sonic (acoustic), temperature, fluid resistivity, and flow meter logs. Density and neutron logs are less commonly used in groundwater investigations because of concerns over the use of radioactive sources in aquifers. The standard suite of geophysical logs, although decades old, still has great value, especially combined with aquifer performance test data and detailed lithological data from well cuttings. Care must also be taken to obtain high-quality (i.e., calibrated and standardized) logs and the project team should include an experienced professional to process and qualitatively and quantitatively interpret the logs. Local geophysical loggers are present in most areas of Canada and the United States that can run at least some of the basic geophysical logs.

Advanced geophysical logging allows for borehole wall imaging, identification of mineral phases, improved quantification of porosity, and measurement of permeability (hydraulic conductivity). Applications of advanced borehole geophysical logging to ASR and other MAR projects were reviewed by Shawky (2006) and Maliva et al. (2009), but the technology has wider applications to alternative water supply and injection well projects in general. Logs that have great potential value for water-resources investigations include nuclear magnetic resonance, microresistivity imaging, and elemental capture spectroscopy.

Nuclear magnetic resonance logging

Nuclear magnetic resonance (NMR) logging provides a measure of the total fluid-filled porosity and pore-size distribution of a formation. The NMR tool contains a large permanent magnet that aligns (polarizes) the non-lattice bound hydrogen atoms (protons) in the formation. The protons occur almost entirely in water molecules in a groundwater system. A series of magnetic pulses generated by the logging tool causes the protons to precess around the direction of the polarization field. The precessing protons create oscillating magnetic fields that generate weak radio signals, which are measured by the NMR tool. The signal decays exponentially with a characteristic time constant (T_2), which is called the transverse relaxation or decay time. The rate of relaxation of the precessing protons is caused in part by grain surface interactions and is thus inversely related to pore size. Using empirical algorithms, the total porosity and pore size distribution can be estimated. NMR log can thus provide data on the bound and moveable water distribution (i.e., effective porosity), and be further processed to estimate permeability and hydraulic conductivity. The NMR log can provide quantitative information on the location and properties of potential flow and confining strata.

Microresistivity imaging logging

Microresistivity imaging logs can produce high-resolution images of the borehole based on numerous microresistivity measurements. An applied voltage causes an alternating current to flow from each electrode button on the sonde through the formation to a receiver electrode located higher on the sonde. As the current emerges from the button on a tool pad or flap, its path is initially focused on a small volume of the formation directly facing the button. A microresistivity image of the borehole wall is created from the current measured by the array of buttons. Microresistivity logs allow for the visualization of fractures, sedimentary structures, breccias, and slumped intervals, and the image can be processed to identify fractures and determine their orientation and aperture width. Large pores and vugs (i.e., macroporosity) can be identified and their abundance quantified.

Elemental Capture Spectroscopy

Elemental capture spectroscopy logging is similar to neutron logging in that a neutron source is used to emit neutrons into the formation and gamma rays released as the result of the collision and interaction of the emitted neutrons with atomic nuclei in the formation are detected. Either a radioactive neutron source or a pulsed electronic neutron generator may be used. Elemental capture spectroscopy differs in that the full spectrum of gamma rays generated from neutron-element interactions is measured. The measured gamma ray energy spectrum is processed using an algorithm to deconvolute the gamma ray contributions from specific elements based on known detector responses for each important constituent. The relative elemental spectral yields are then converted to dry weight elemental concentrations using an oxide closure method. The elemental concentrations are further processed to provide dry-weight mineralogies using empirical relationships derived from core chemistry and mineralogical databases. The log can be used to differentiate between rock types such as shales, sandstones, limestones, and dolostones.

Workflow Software

Advanced borehole geophysical logging techniques have been applied to ASR projects in Texas, Florida (several sites), and the United Arab Emirates and to a brackish-water supply investigation in Florida. Advanced borehole geophysical logs by themselves can provide much useful information on aquifer hydraulic and petrophysical properties, mineralogy, and chemistry. However, for some projects much of the potential value of the logs was not realized. Numerical groundwater modeling is now the standard method for evaluating groundwater resources. A goal for groundwater investigations should be to incorporate all collected aquifer testing, pressure (head), water quality, geological, and geophysical data into the development of both conceptual and numerical models of aquifer systems. Workflow software (e.g., Petrel) can be used to integrate various types of data into a single groundwater flow model, including the MODFLOW family of codes. For example, hydraulic conductivity and porosity data from NMR logs can be integrated over a specific depth interval to obtain transmissivity and average porosity values for the interval. A major advantage of workflow software is that models can be continuously updated as new data become available.

Conclusions

Advanced borehole geophysical logging is complementary to, but cannot fully replace, standard aquifer performance testing for aquifer characterization. The latter is needed to obtain information on aquifer transmissivity, storativity, and leakance. Advanced geophysical logs may be performed in lieu of standard pump testing in mud-filled boreholes and in situations where saline-water disposal posses environmental problems. Data on porosity types and distribution, and fine-scale variations in aquifer hydraulic conductivity and aquifer composition can be imported directly into geological data management or workflow software and, in turn, groundwater flow and solute-transport models. Application of advanced technologies to groundwater resources management and development projects should be justifiable in terms of costs versus benefits. The greatest potential value of advanced borehole geophysical logging is for projects where solute transport is critical (e.g., ASR, salinity barrier, and injection well systems and brackish-water wellfields for desalination plants), and where more refined aquifer characterization and modeling may reduce the risk of a failed or under-performing system.

References

Driscoll, F.G., 1986, Groundwater and Wells, 2nd Edition: Johnson Filtration Systems, St. Paul, Mn, 1089 p.

Keys, W.S., 1989, Borehole geophysics applied to ground water investigations: National Water Well Association, Dublin, Ohio, 313 p.

Keys, W.S., 1990, Borehole geophysics applied to ground-water investigations: Techniques of Water-Resources Investigations of the United States Geological Survey, Book 2, Chapter E2, 150 p.

Keys, W.S., 1997, A practical guide to borehole geophysics in environmental investigations: Lewis Publishers, Boca Raton, FL 192 p.

Kobr, M., Mareš, S, and Paillet, F., 2005, Borehole geophysics for hydrogeological studies: principles and applications, in Rubin, Y., and Hubbard, S.S. (eds.) Hydrogeophysics, Springer, Netherlands, p. 291-331.

Maliva, R. G., Clayton, E. A., and Missimer, T. M., 2009, Application of advanced borehole geophysical logging to managed aquifer recharge investigations: Hydrogeology Journal, v. 17, no. 6, p. 1547-1556OI 10.1007/s10040-009-04737-z.

Maliva, R.G., Guo, W., and Missimer, T.M., 2006, Aquifer storage and recovery: Recent hydrogeological advances and system performance: Water Environment Research, v. 78, p. 2428-2435.

Maliva, R.G., and Missimer, T.M., 2008, ASR, useful storage, and the myth of residual pressure: Ground Water, v. 46, p. 171.

Pearce, F., 2006, When Rivers Run Dry: Beacon Press, Boston MA, 324 p.

Shawky, I., 2006, Application of most recent borehole geophysical logging for aquifer characterization, *In* Recharge systems for protecting and enhancing groundwater resources, Proceedings of the 5th International Symposium on Management of Aquifer Recharge, Berlin, Germany, 11-16 June 2005, UNESCO, Paris, p. 467-473.