USGS
science for a changing world

Florida Integrated Science Center

Borehole Geophysical Logging Program: Incorporating New and Existing Techniques in Hydrologic Studies

Overview

The borehole geophysical logging program at the U.S. Geological Survey (USGS)-Florida Integrated Science Center (FISC) provides subsurface information needed to resolve geologic, hydrologic, and environmental issues in Florida. The program includes the acquisition, processing, display, interpretation, and archiving of borehole geophysical logs. The borehole geophysical logging program is a critical component of many FISC investigations, including hydrogeologic framework studies, aquifer flow-zone characterization, and freshwater-saltwater interface delineation.

New Borehole Geophysical Logging Capabilities in Florida

In addition to acquiring standard borehole-log information such as caliper, gamma, spontaneous potential, and electromagnetic induction data (table 1), FISC utilizes new technologies and procedures to generate advanced logs. Of particular importance are digital borehole imaging and electromagnetic flowmeter logging, both of which are now used to augment existing techniques.

Digital borehole optical televiewers equipped with a high-resolution cameras can create detailed, 360-degree images of borehole walls and simultaneously collect borehole deviation data. The digital borehole images can be used to (1) accurately determine the depths for a well completion interval, (2) position a recovered core to its proper depth, (3) acquire a high-resolution borehole image that serves as a surrogate for intervals having no core recovery (Ward and others, 2003), and (4) characterize aquifer pore systems. Fracture and bedding plane orientations can also be determined, because borehole images can be oriented to magnetic north. In combination with a new digital log acquisition system, a digital borehole image can be acquired at relatively high logging speeds (about 3-15 feet per minute, depending on desired pixel density). Various log presentation software can be used to display these images, as well as standard logs on multilog-paper displays up to 36 inches wide. A digital copy of the display can be viewed on a computer using nonproprietary software readers.

To address difficulties in accurately quantifying relative transmissivity in aquifer flow zones, FISC is now using an electomagnetic flowmeter to accurately measure flow at intermediate velocities. Previously, heat pulse flowmeters and spinner flowmeters were solely used to measure flow across all velocities. Heat pulse flowmeters, however, can only measure low-velocity flow and do not generate continuous logs. Spinner flowmeters adequately measure high velocity flow and generate continuous logs, but quantifying the amount of flow from spinner revolutions is time consuming and difficult. The electromagnetic flowmeter accurately measures medium flow velocities, generates a continuous log of flow velocity and direction, and can make stationary measurements like the heat pulse flowmeter. The logs generated by the electromagnetic flowmeter can help show the relative transmissivity of flow zones within a well. A fluid meter built into the tool also displays changes in temperature and fluid resistivity, which also aids in the identification of flow zones.

Although most borehole geophysical log acquisition is performed from a vehicle, equipment portability also allows easy transport to remote well sites, such as those in offshore marine or wetland environments. Wells up to 3,200 feet deep and greater than 2 inches in diameter can be accommodated, providing access to all major aquifers in Florida, including much of the Floridan aquifer system.

FISC Hydrologic Investigations Employing Borehole Geophysical Logging Techniques

Geophysical logs run in exploratory or investigative boreholes can provide valuable hydrogeologic information, especially in areas with poor lithologic and (or) hydrologic control. Geophysical logs also can provide much needed information to help in determining the correct placement of well completion depths or intervals. The acquisition of borehole geophysical logs can become the determining factor in solving complex subsurface issues. The following studies highlight new and existing techniques used by FISC to resolve geologic, hydrologic, and environmental issues.

Hydrogeologic Framework Studies

Partially recovered core samples typically can only be placed within a 5- to 10-foot range of core barrel depth. Placement of core material or recognition of void space within these poor recovery intervals is often difficult using examination of the core and standard borehole geophysical methods. With the aid of a digital optical borehole image log, a trained user can accurately reconstruct core sample depths (Ward and others, 2003) and use image log data to aid in pore-type characterization (including large cavities) for both intervals with and without recovered core. Cunningham and others (2004a, b; 2006a, b) used digital images to identify lithology, pore type, and zones of concentrated groundwater flow to show the connection between stratigraphy and the development of porosity and permeability within the Biscayne aquifer. Further study led to the development of a multilayer, conceptual hydrogeologic framework for the Biscayne aquifer along the Everglades-Urban corridor (Lake Belt area) in northwestern Miami-Dade County (Cunningham and others, 2006a).

Digital optical borehole imagery was used in combination with core data to construct stratigraphic sections that show the areal extent of macroporous flow zones within the Miami-Dade Northwest Well Field (Renken and others, 2005; 2008). Tracer tests conducted during 2003-04 at the well field demonstrated the continuity of touching-vug flow zones and the potential for rapid, long-distance chemical and colloidal transport within the Biscayne aquifer (Shapiro and others, 2008; Harvey and others, 2008). Digital optical borehole imagery was used to determine the dimensions of macropores, and was also used with core data to develop hydrostratigraphic cross sections to help show the connectivity of macroporosity between wells. Previous studies may have underestimated the porosity, as well as the areal extent of macroporosity.

Aquifer Flow-Zone Characterization

Borehole fluid temperature and conductivity logs collected during one of the Miami-Dade Northwest Well Field tracer tests have been used to illustrate well-to-well tracer movement within preferential flow zones (Cunningham and others, 2006b; Renken and others, 2008). Observation well borehole fluid temperature logs were used to show that a single flow zone constitutes the dominant horizon for well-to-well hydraulic interconnection and for the migration of most of the tracer mass (fig. 1). The observed monotonic increase in temperature with depth shortly after injection (1252 hours) suggests that conservative tracers traveling within the shallow flow zone approximately 41 feet below land surface arrived at the observation well prior to tracers traveling within touching-vug pore zones at greater depths (Renken and others, 2008).

Table 1. Available geophysical logs for use in FISC research.

[cps, counts per second; EM, electromagnetic; FISC, Florida Integrated Science Center; ft/min, foot per minute; gal/min, gallon per minute; PVC, polyvinyl chloride]

Geophysical logging tool and log type	Tool use	Interpretive value of log
Borehole deviation	Measures deviation of borehole from vertical.	Used as input for calculation of true vertical depth.
Borehole fluid	Generates logs of water-quality properties that include the following: borehole fluid temperature, resistivity, conductivity, specific conductance, salinity, pressure, redox, dissolved oxygen concentration, and pH.	Identification of ground-water flow zones penetrated by the borehole and sources of incoming water.
Caliper	Measures borehole diameter, using mechanical, three-arm, or high-resolution acoustic caliper.	Determination of cavity size and geometry.
Digital, optical and acoustic borehole image	Televiewer creates digital, optical and acoustic images of borehole wall or casing.	Used to reference core to original depth, detect cavities, faults, and fractures, as well as characterize pore systems. Optical and acoustic log types can be aligned to magnetic north and exported in BITMAP format.
Electromagnetic induction	Measures formation conductivity in both cased and uncased wells. Produces a formation resistivity log using the inverse relations with conductivity.	Determination of depth to freshwater-saltwater interface in boreholes. Help identify zones of ground-water flow.
Flowmeter	Measures vertical fluid flow within a borehole. Measures flow under both ambient and pumping conditions. Tool choice is based on fluid flow velocity: (1) heat pulse flowmeter (units in gal/min) for flows less than 1.5-0.03 gal/min, (2) spinner flowmeter (units in cps) for flows greater than 6.5 ft/min, and (3) EM flowmeter (units in gal/min or ft/min) measures a wide range of flow velocities (0.01-10.6 gal/min).	Identification of ground-water flow zones penetrated by the borehole and determination of relative transmissivity of flow zones.
Full waveform sonic	Measures acoustic wave travel time through borehole fluid and the surrounding rocks. Post processing creates compressional, shear, and Stoneley-wave logs.	Compressional velocity logs are used to create a sonic porosity log with either the Raymer-Hunt or Wylie equations. Stoneley-wave amplitude log is used to estimate permeability. Additional processing yields cement bond logs, as well as logs showing various engineering properties, and synthetic seismic wiggle traces.
Natural-gamma	Measures gamma radiation of natural radioisotopes in surrounding formation (output is in cps).	Correlation of lithologic units between wells.
Spontaneous potential and single-point resistance	Measures the natural potential that originates from electrochemical differences between borehole and formation fluids at lithologic boundaries. Requires an open borehole.	Used to infer lithologic changes. Single-point resistance log can be used to detect sections of slotted casing in completed wells.

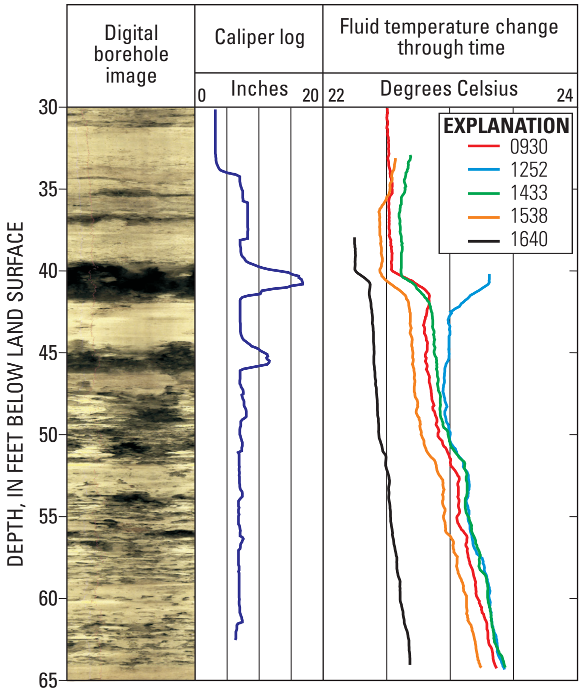

Figure 1. Temporal change in borehole temperature caused by the migration of a tracer within a touching-vug flow zone at a depth of 41 feet below land surface in an observation well (modified from Renken and others, 2008). Tracer injection occurred at 0930 hours. Fluid temperature log at 1252 hours was not completed because the top of the logging tool was lodged against the casing bottom.

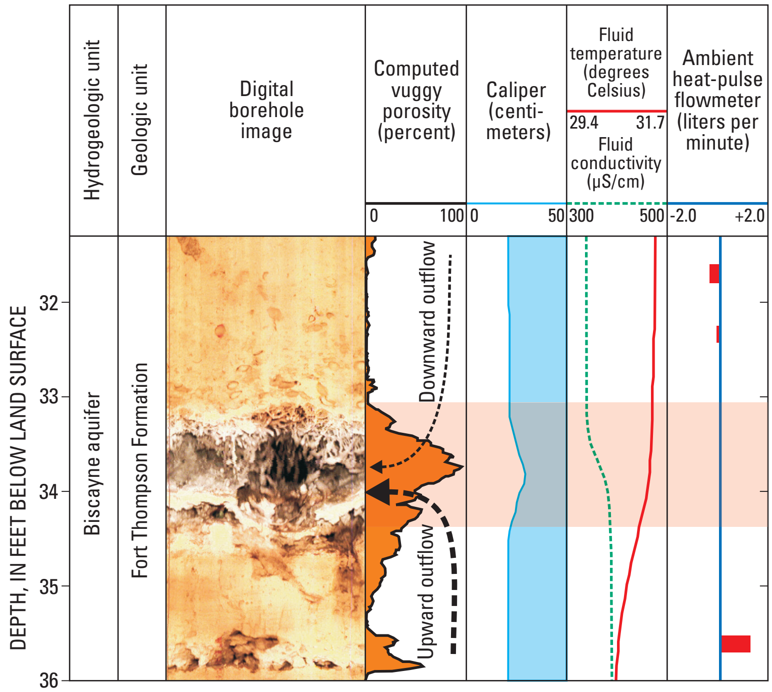

Figure 2. Comparison of borehole image, computed vuggy porosity, geophysical, and flowmeter logs for the G-3788 test corehole showing evidence of water outflow from the borehole into a preferential flow zone. Abbreviation µS/cm is microsiemens per centimeter.

High-resolution heat pulse, electromagnetic, and spinner flowmeters are routinely used by FISC scientists to measure vertical fluid flow within a borehole over a wide range of flow rates and under both ambient and pumping conditions. Borehole flowmeter measurements have been used to identify permeable flow zones in the Biscayne aquifer (Cunningham and others, 2004a; 2006a), and assess vertical hydraulic gradients. Flowmeter measurements combined with data from digital borehole images and fluid-temperature and conductivity logs can be used to accurately evaluate and characterize flow zones within the context of a high-resolution conceptual hydrogeologic framework (fig. 2). As an example, Cunningham and others (2004b) used ambient flowmeter and borehole fluid-temperature and conductivity logs to hypothesize sources of ground-water recharge. Data from flowmeter and borehole-fluid logs collected in seven wells along an 8-mile reach of the L-31 Canal in Miami-Dade County were used to identify sections that were consistent with aquifer recharge by surface water from Everglades National Park. Horizontal flowmeters were also placed within preferential flow zones of the Biscayne aquifer identified by digital borehole images during this study (Cunningham and others, 2004b) as part of a continuous ground-water monitoring program operated by the South Florida Water Management District. The real-time flow data (which are still being analyzed) from these horizontal flowmeters show variable ground-water flow directions and rates. These data, along with data from Cunningham and others (2004b), were later used to further hypothesize that nearby ground-water pumpage in excess of the permitted allotment was also influencing recharge.

Freshwater-Saltwater Interface Delineation

Electromagnetic induction logs have been used to obtain detailed vertical profiles of the conductivity of the aquifer around each well, and used in combination with surface-geophysical methods and chloride concentration data, to map the position of the saltwater interface in southeastern Florida (Hittle, 1999). Detection and monitoring of the saltwater front through induction logging in cased wells over time is an ongoing effort by the USGS and State, county, and municipal cooperators. The induction logging tool measures the bulk electrical conductivity of rock and pore fluids to delineate lithology, porosity, and fluid salinity within open and polyvinyl chloride (PVC)-cased boreholes. Within these casings, this logging tool can measure changes in the dissolved-solids concentration of pore fluid over time. Data collected from USGS monitoring wells as part of the ongoing induction logging program indicate that interface movement is irregular within the vertical section of the well, and possibly related to differential lateral movement of brackish to saline water within zones of higher permeability (fig. 3).

References Cited

Cunningham, K.J., Carlson, J.L., Wingard, G.L., Robinson, E., and Wacker, M.A., 2004a, Characterization of aquifer heterogeneity using cyclostratigraphy and geophysical methods in the upper part of the Biscayne aquifer, southeastern Florida: U.S. Geological Survey Water Resources Investigations Report 03-4208, 66 p. (Also available online at *http://sofia.usgs.gov/projects/aq_heterogeneity/)*

Cunningham, K.J., Wacker, M.A., Robinson, E., Gefvert, C.J., and Krupa, S.L., 2004b, Hydrology and ground-water flow at Levee 31N, Miami-Dade County, Florida, July 2003 to May 2004: U.S. Geological Survey Scientific Investigations Map I-2846, 1 pl. (Also available online at *http://sofia.usgs.gov/projects/seep_mgmt/)*

Cunningham, K.J., Wacker, M.A., Carlson, J.L., Robinson, E., Dixon, J.F., and Wingard, G.L., 2006a, A cyclostratigraphic and borehole geophysical approach to development of a three-dimensional conceptual hydrogeologic model of the karstic Biscayne aquifer, southeastern Florida: U.S. Geological Survey Scientific Investigations Report 2005-5235, 69 p., plus appendixes. (Also available online at *http://pubs.usgs.gov/sir/2005/5235/)*

Cunningham, K.J., Renken, R.A., Wacker, M.A., Zygnerski, M.R., Robinson, E., Shapiro, A.M., and Wingard, G.L., 2006b, Application of carbonate sequence stratigraphy to delineate porosity, preferential flow, and advective transport in the karst limestone of the Biscayne aquifer, SE Florida, USA, *in* Harmon, R.S., and Wicks, Carol, eds., 2006, Perspectives on Karst Geomorphology, Hydrology and Geochemistry—A Tribute Volume to Derek C. Ford and William B. White: Geological Society of America Special Paper 404, p. 191-208.

Harvey, R.W., Metge, D.W., Shapiro, A.M., Renken, R.A., Osborn, C.L., Ryan, J.N., Cunningham, and Landkamer, L., 2008, Pathogen and Chemical Transport in the Karst Limestone of the Biscayne Aquifer: 3. Use of microspheres to estimate the transport potential of *Cryptosporidium parvum* oocysts: Water Resources Research, v. 44, W08431, doi: 1029/2007WR006060.

Hittle, C.D., 1999, Delineation of saltwater intrusion in the surficial aquifer system in eastern Palm Beach, Martin, and St. Lucie Counties, Florida, 1997-98: U.S. Geological Survey Water-Resources Investigations Report 99-4214, 1 sheet.

Renken, R.A., Shapiro, A.M., Cunningham, K.J., Harvey, R.W., Metge, D.W., Zygnerski, M.R., Osborn, C.L., Wacker, M.A., and Ryan, J.N., 2005, Assessing the vulnerability of a municipal well field to contamination in a karst aquifer: Environmental and Engineering Geoscience, v. 11, no. 4, p. 319-331.

Renken, R.A., Cunningham, K.J., Shapiro, A.M., Harvey, R.W., Zygnerski, M.R., Metge, D.W., and Wacker, M.A., 2008, Pathogen and Chemical Transport in the Karst Limestone of the Biscayne Aquifer: 1. Revised Conceptualization of Groundwater Flow: Water Resources Research, v. 44, W08429, doi: 1029/2007WR006058.

Shapiro, A.M., Renken, R.A., Harvey, R.W., Zygnerski, M.R., Metge, D.W., 2008, Pathogen and Chemical Transport in the Karst Limestone of the Biscayne Aquifer: 2. Chemical retention from diffusion and slow advection: Water Resources Research, v. 44, W08430, doi: 1029/2007WR006059.

Ward, W.C., Cunningham, K.J., Renken, R.A., Wacker, M.A., and Carlson, J.I., 2003, Sequence-stratigraphic analysis of the Regional Observation Monitoring Program (ROMP) 29A test corehole and its relation to carbonate porosity and regional transmissivity in the Floridan aquifer system, Highlands County, Florida: U.S. Geological Survey Open-File Report 03-201, 34 p., plus appendixes. (Also available online at *http://fl.water.usgs.gov/Abstracts/ofr03_201_ward.html)*

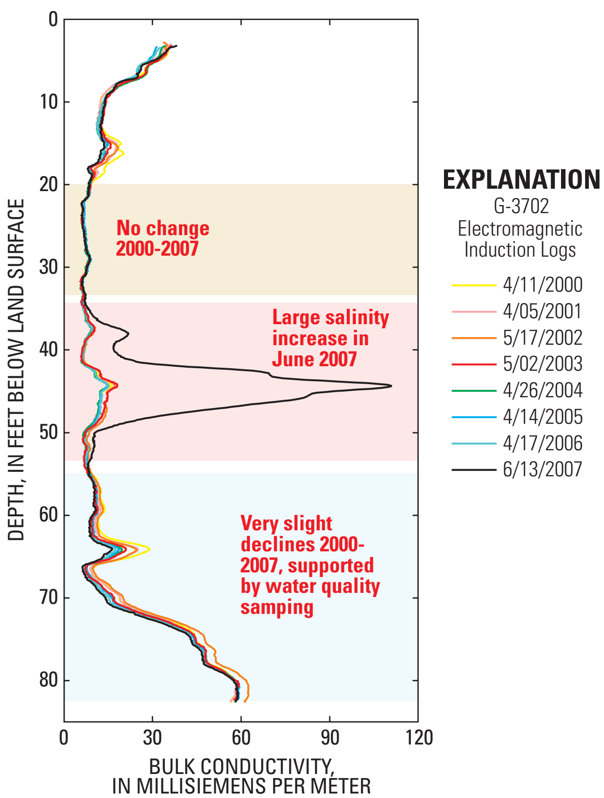

Figure 3. Comparison of electromagnetic-induction logs collected in well G-3702 from April 2000 through May 2007 along Black Creek Canal in Miami-Dade County (Scott Prinos, U.S. Geological Survey, written commun., 2008). An increase in conductivity is evident between 40 and 50 feet.

—*Michael A. Wacker and Kevin J. Cunningham*

For more information, please contact:

Michael A. Wacker
e-mail: mwacker@usgs.gov

Kevin J. Cunningham
e-mail: kcunning@usgs.gov

U.S. Geological Survey
Florida Integrated Science Center
(FISC—Ft. Lauderdale)
3110 SW 9th Ave.,
Ft. Lauderdale, FL 33315