STAFF EXHIBIT 28

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U.S. Department of the Interior
U.S. Geological Survey

An Evaluation of Borehole Flowmeters Used to Measure Horizontal Ground-Water Flow in Limestones of Indiana, Kentucky, and Tennessee, 1999

By John T. Wilson[1], Wayne A. Mandell[2], Frederick L. Paillet[3], E. Randall Bayless[1], Randall T. Hanson[4], Peter M. Kearl[5], William B. Kerfoot[6], Mark W. Newhouse[4], and William H. Pedler[7]

Prepared in cooperation with the U.S. Army Environmental Center, Environmental Restoration [illegible]

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In the Matter of U.S. Army (Jefferson Proving Ground)
Docket No. 40-8838-MLA Official Exhibit No. 28
OFFERED by: Applicant/Licensee Intervenor ______
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Water-Resources Inv[illegible]

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Indianapolis, Indiana
2001

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[6]K-V Associates, Inc., Mashp[illegible]
[7]RAS, Inc., Golden, Colorado

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U.S. DEPARTMENT OF THE INTERIOR
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Abstract

Three borehole flowmeters and hydrophysical logging were used to measure ground-water flow in carbonate bedrock at sites in southeastern Indiana and on the west-central border of Kentucky and Tennessee. The three flowmeters make point measurements of the direction and magnitude of horizontal flow, and hydrophysical logging measures the magnitude of horizontal flow over an interval. The directional flowmeters evaluated include a horizontal heat-pulse flowmeter, an acoustic Doppler velocimeter, and a colloidal borescope flowmeter. Each method was used to measure flow in selected zones where previous geophysical logging had indicated water-producing beds, bedding planes, or other permeable features that made conditions favorable for horizontal-flow measurements.

Background geophysical logging indicated that ground-water production from the Indiana test wells was characterized by inflow from a single, 20-foot-thick limestone bed. The Kentucky/Tennessee test wells produced water from one or more bedding planes where geophysical logs indicated the bedding planes had been enlarged by dissolution. Two of the three test wells at the latter site contained measurable vertical flow between two or more bedding planes under ambient hydraulic head conditions.

Field measurements and data analyses for each flow-measurement technique were completed by a developer of the technology or by a contractor with extensive experience in the application of that specific technology. Comparison of the horizontal-flow measurements indicated that the three point-measurement techniques rarely measured the same velocities and flow directions at the same measurement stations. Repeat measurements at selected depth stations also failed to consistently reproduce either flow direction, flow magnitude, or both. At a few test stations, two of the techniques provided similar flow magnitude or direction but usually not both. Some of this variability may be attributed to naturally

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occurring changes in hydraulic conditions during the 1-month study period in August and September 1999. The actual velocities and flow directions are unknown; therefore, it is uncertain which technique provided the most accurate measurements of horizontal flow in the boreholes and which measurements were most representative of flow in the aquifers.

The horizontal heat-pulse flowmeter consistently yielded flow magnitudes considerably less than those provided by the acoustic Doppler velocimeter and colloidal borescope. The design of the horizontal heat-pulse flowmeter compensates for the local acceleration of ground-water velocity in the open borehole. The magnitude of the velocities estimated from the hydrophysical logging were comparable to those of the horizontal heat-pulse flowmeter, presumably because the hydrophysical logging also effectively compensates for the effect of the borehole on the flow field and averages velocity over a length of borehole rather than at a point. The acoustic Doppler velocimeter and colloidal borescope have discrete sampling points that allow for measuring preferential flow velocities that can be substantially higher than the average velocity through a length of borehole. The acoustic Doppler velocimeter and colloidal borescope also measure flow at the center of the borehole where the acceleration of the flow field should be greatest.

Of the three techniques capable of measuring direction and magnitude of horizontal flow, only the acoustic Doppler velocimeter measured vertical flow. The acoustic Doppler velocimeter consistently measured downward velocity in all test wells. This apparent downward flow was attributed, in part, to particles falling through the water column as a result of mechanical disturbance during logging. Hydrophysical logging yielded estimates of vertical flow in the Kentucky/Tennessee test wells. In two of the test wells, the hydrophysical logging involved deliberate isolation of water-producing bedding planes with a packer to ensure that small horizontal flow could be quantified without the presence of vertical flow. The presence of vertical flow in the Kentucky/Tennessee test wells may preclude the definitive measurement of horizontal flow without the use of effective packer devices. None of the point-measurement techniques used a packer, but each technique used baffle devices to help suppress the vertical flow. The effectiveness of these baffle devices is not known; therefore, the effect of vertical flow on the measurements cannot be quantified.

The general lack of agreement among the point-measurement techniques in this study highlights the difficulty of using measurements at a single depth point in a borehole to characterize the average horizontal flow in a heterogeneous aquifer. The effective measurement of horizontal flow may depend on the precise depth at which measurements are made, and the measurements at a given depth may vary over time as hydraulic head conditions change. The various measurements also demonstrate that the magnitude and possibly the direction of horizontal flow are affected by the presence of the open borehole. Although there is a lack of agreement among the measurement techniques, these results could mean that effective characterization of horizontal flow in heterogeneous aquifers might be possible if data from many depth stations and from repeat measurements can be averaged over an extended time period. Complications related to vertical flow in the borehole highlights the importance of using background logging methods like vertical flowmeters or hydrophysical logging to characterize the borehole environment before horizontal-flow measurements are attempted. If vertical flow is present, a packer device may be needed to acquire definitive measurements of horizontal flow.

Because hydrophysical logging provides a complete depth profile of the borehole, a strength of this technique is in identifying horizontal- and vertical-flow zones in a well. Hydrophysical logging may be most applicable as a screening method. Horizontal-flow zones identified with the hydrophysical logging then could be evaluated with one of the point-measurement techniques for quantifying preferential flow zones and flow directions.

Additional research is needed to determine how measurements of flow in boreholes relate to flow in bedrock aquifers. The flowmeters may need to be evaluated under controlled laboratory conditions to determine which of the methods accurately measure ground-water velocities and flow directions. Additional research also is needed to investigate variations in flow direction with time, daily changes in velocity, velocity corrections for fractured bedrock aquifers and unconsolidated aquifers, and directional differences in individual wells for hydraulically separated flow zones.

Introduction

Borehole geophysical methods help determine the lithologic and structural characteristics of bedrock aquifers. Borehole flowmeters, whether vertical or horizontal, can be used to identify water-producing zones in an open bedrock well. Some horizontal flowmeters have the additional benefit of being able to measure the direction of flow through the borehole. The ability to measure directional horizontal ground-water flow in observation wells has numerous applications to site-specific studies of ground water. Two uses of measured ground-water-flow directions are site assessment and remediation planning for ground-water-contamination studies and determining the placement of additional observation wells. Ground-water-flow velocities and directions can be used to help develop and calibrate ground-water-flow models, supplement or replace natural and forced-gradient tracer tests, assess intra-borehole flow, assess flow connections during cross-hole tests and, when combined with other geophysical logs, aid in the detailed interpretation of the hydrogeologic framework.

The U.S. Army Environmental Center (USAEC) oversees the environmental restoration of army bases throughout the United States. Many of the bases are in areas of karst terrain, where carbonate bedrock (limestone and dolomite) have been modified by fracturing and dissolution by water. The USAEC needs to identify techniques and quantify remedial parameters as part of the overall environmental-restoration process. Defining hydrogeologic settings in karst terrains is a difficult process because of the inherently complex nature of karst systems. Through experience in working with karst systems, the USAEC is developing special techniques for dealing with the unique circumstances presented by such systems. Knowledge of the available flowmeter techniques and how they perform in carbonate bedrock would be beneficial to the USAEC for technical oversight of the environmental-restoration process. Therefore, the U.S. Geological Survey (USGS), in cooperation with the Environmental Restoration Division of the USAEC, began a study in 1999 to evaluate four techniques for measuring horizontal ground-water flow in uncased boreholes completed in carbonate bedrock. Wells for testing the flowmeters were selected from available wells at two military reservations, Jefferson Proving Ground (JPG) in southeastern Indiana and Fort Campbell (FC) in southwestern Kentucky/northwestern Tennessee.

Background

Borehole camera, acoustic-televiewer, caliper, and other geophysical logs can identify bedding planes, fractures, and other lithologic or dissolution features that might be conduits for ground-water flow and solute transport. These borehole tools (except the borehole camera under ideal conditions) cannot identify the actively flowing conduits in

When the flowmeter control panel is on, each thermistor continuously sends its voltage-based temperature to the control panel. The control panel routes the incoming thermistor information and delivers a machine-unit readout on the control panel that represents the arithmetic difference between diametrically paired thermistors. Each set of diametrically paired thermistors is positioned during construction of the probe to geometrically subdivide a horizontal plane into equal parts, totaling 360 degrees in a circle (fig. 1d). Magnetic north at each site is obtained by fitting a compass to the top of the connecting rods that hold the flowmeter probe in place; a particular pair of thermistors on the probe then is referenced to magnetic north. Consequently, each pair of thermistors corresponds to a designated geographic direction.

Following placement of the probe, the water column in the borehole is allowed to reach equilibrium before measurements are made. Equilibrium is determined when changes in the control-panel readout minimize over time and the water level stabilizes. Insertion of the probe into the water column is analogous to a small-scale "slug test" because the borehole water is displaced by the probe and rods. Consequently, to avoid the contribution of external forces to flowmeter measurements, proper equilibration time is essential. As with a slug test, less permeable aquifers take more time for the water column to equilibrate.

After equilibrium is achieved, an initial set of machine-unit readings is recorded. Immediately following, the heat-pulse switch on the control panel is activated; activation creates a single point-source heat pulse at the center of the probe inside the fuzzy packer. The heat pulse lasts for a designated time (generally 28 seconds), after which the dissipation or convection of the heated water is measured for 3 minutes. The final set of machine-unit values is read from the control panel at a designated time following the heat pulse.

After the initial readings and activation of the heat pulse, the heat spherically dissipates in the water from the heat source through the glass beads in the fuzzy packer. Under the additional force of ground-water flow in the borehole and fuzzy packer, however, spherical heat dissipation is shifted in the direction of ground-water flow. Consequently, the migration of the heat pulse is sensed as a larger increase in temperature by the thermistors in the direction of ground-water flow. The magnitude of heat transfer decreases with the cosine of the angle from the main axis of flow.

Each flowmeter readout consists of two sets of recordings—a "before" and "after" heat-pulse reading for the responses from each pair of thermistors. Each of these readings represents the temperature differences between the thermistors in each pair. The KVA flowmeter analysis uses a graphical method to verify that the thermistor-response pattern across the array matches the expected pattern for uniform convective flow. If the individual thermistor-response differences cannot be fit to such a pattern, the data imply that there is negligible net flow across the borehole and a flow direction and velocity cannot be determined.

The interpretation of results obtained with the KVA flowmeter is based on a study by Wheatcraft and Winterberg (1985), who determined that a uniform flow system around a permeable cylinder (borehole) is defined by one parameter (K_r), which is the contrast in hydraulic conductivity between the borehole and surrounding media. Their study of streamline refraction at the cylinder boundary indicated very little refraction for hydraulic-conductivity contrasts of less than 50 percent. The hydraulic conductivity of the external media and fuzzy packer are often different and may result in refraction of flow streamlines in the fuzzy packer. The refracting streamlines indicate changes in flow velocities. To offset changes in flow velocities from differential conductivities between the fuzzy packer and the surrounding media, the flowmeter is calibrated in a flow chamber. Flowmeter calibration recreates well construction and surrounding media conditions and thus determines the sensitivity of the instrument to various differential conductivities based on known ground-water-flow rates pumped through a calibration chamber.

For open boreholes or sand-packed screens (2-inch- or 4-inch-diameter), hydraulic-conductivity and porosity corrections should be made to adjust probe readings to flow conditions in the aquifer. The fuzzy packer for the KVA GeoFlo Model 40 probe contains uniform glass beads of 2-millimeter-diameter. The approximate hydraulic conductivity within the beads is 2,000 ft/d, and the porosity is 30 percent. The screen and polymer pile of the fuzzy packer reduce the flow of water by about two-thirds, resulting in a hydraulic conductivity of 670 ft/d for the entire packer. If the combined hydraulic conductivity of the glass beads and fuzzy packer is greater than 20 times the hydraulic conductivity of the aquifer, the magnification of flow approaches an asymptotic maximum value of 2 times that of the aquifer (Kerfoot, 1988). Refer to Kerfoot (1988) for a detailed explanation of the calibration procedures and methods that use the calibration chamber.

For the purposes of this study, the velocities measured in the borehole were adjusted to the seepage velocity of the aquifer by solving for the flow-magnification factor. The magnification factor refers to the increased velocity in the borehole compared with the velocity when the hydraulic conductivity inside and outside the borehole is equal. According to Wheatcraft and Winterberg (1985), the magnification factor f is

$$f = (2K_r)/(1 + K_r), \tag{1}$$

where K_r is the ratio of hydraulic conductivity between the open borehole and the outside media or aquifer.

With the KVA flowmeter in the borehole, the hydraulic conductivity of the borehole is the hydraulic conductivity of the fuzzy packer. The ratio of hydraulic conductivities can be expressed as

$$K_r = \frac{K_{i+a}}{K_o}. \tag{2}$$

where K_{i+a} is the hydraulic conductivity of the internal packing (glass beads) and the porous lining of the fuzzy packer (i) combined with the hydraulic conductivity of the annular packing around the well screen (a), and

K_o is the hydraulic conductivity of the outside media or aquifer.

If the packer is placed in a well screen, the screen resistance automatically is included in the correction determined with the calibration chamber. For open boreholes, the packer is positioned by video camera in a fractured part of the borehole. If a double-packer slug test or drawdown test has been completed previously, an approximate hydraulic conductivity (K_o) is known for the fracture zone. Equation 1 was solved for the conditions in the calibration chamber and the field conditions. The ratio of f for the calibration chamber and f for the field conditions was taken as the correction factor. Estimates of the field hydraulic conductivities (K_o) were based on the values of transmissivity estimated from the vertical-flow logging (table 1, p. 26). The value of (K_{i+a}) was taken as 670 ft/d—the hydraulic conductivity of the glass beads inside the fuzzy packer and the porous lining and housing of the fuzzy packer.

The KVA flowmeter has a velocity-measuring range of 0.1 ft/d to 500 ft/d in well screens and 0.01 ft/d to 500 ft/d if placed in native soil without screen resistance. The KVA flowmeter can be calibrated to different velocity-measurement ranges to prevent a "washout" of the heat pulse. The capability of the flowmeter to measure horizontal ground-water-flow direction and velocity representative of aquifer conditions relies on the hydraulic connection between the fuzzy packer and the surrounding media. If hydraulic short circuiting occurs across the packer and surrounding formation, localized channeling may occur and resulting streamlines may interfere with obtaining a representative measurement. The KVA flowmeter does not compensate for borehole inclination, which may be a factor with deep wells that deviate from vertical with depth. In uncased wells, the maximum operating depth may be limited by the texture of the borehole wall. Because the fuzzy packer fits against the borehole wall, irregularities on the borehole wall may catch the fuzzy packer and prevent it from passing.

Acoustic Doppler Velocimeter

The acoustic Doppler velocimeter (ADV) for borehole research was developed for the U.S. Environmental Protection Agency by SonTek, Inc., in 1996 (SonTek, 1996). The borehole ADV is a prototype based on the ADV SonTek manufactures for making three-dimensional measurements of flow for oceanic and surface-water applications. A description of the surface-water ADV and an evaluation of its laboratory tests were presented in Kraus and others (1994). As of August 1999, there were only two prototypes of the borehole ADV. Personnel from the USGS San Diego, Calif., office made the measurements and processed the data for this study. The use of the ADV in uncased wells in bedrock was considered experimental. Previous experience with the ADV always was in screened wells in unconsolidated aquifers with relatively high rates of ground-water flow and often was during flow-injection studies as described by Newhouse and Hanson (2000).

The ADV is approximately 4 ft long with a 3-inch outer diameter (fig. 2). Deployed with a standard 4-conductor Century Geophysical cable and drawworks, the ADV runs on direct-current power and transmits a binary signal through a standard RS-232 serial-port connection to DOS-based acquisition software. The software is menu driven with adjustable real-time graphics and digital display of velocity and related data-quality attributes.

Inside the ADV, the electronics are separated into upper and lower parts. The upper part contains the digital-processing electronics on two circuit cards. The lower part contains the compass/tilt sensor and probe electronics. The compass/tilt sensor maintains a fixed alignment with respect to the ADV probe. The ADV uses a flux-gate magnetometer for a compass. Data from the flux-gate magnetometer are processed with velocity data to yield velocities in east, north, and up directions. The ADV probe tip is mounted externally below the housing, along with a guard cage to protect the probe from physical damage. The outer diameter of the guard cage limits deployment to wells with an inner diameter of 3.5 inches or greater.

The probe tip consists of one centrally mounted acoustic emitter and three receivers/transducers positioned on radial arms. The sample volume of the ADV is roughly cylindrical in shape. Volume is a function of the diameter of the transmit transducer (0.177 inch) and user-defined parameters of transmitter-pulse length and receiver-window length that are adjusted with the acquisition software. The focal point of the sample volume is about 1.9 inches in front of (below) the emitter, and the sample volume ranges from 0.008 to 0.028 cubic inches. The frequency of measurement is 25 times per second, resulting in a large particle-tracking data base that includes X, Y, and Z directions (corresponding to east, north, and up in the borehole coordinate system); pitch from vertical; signal-to-noise ratio; and a correlation factor.

The ADV does not measure fluid velocity directly but tracks the velocity of suspended particles in the water column. Real-time graphic and tabular displays by the data-acquisition software allow the user to monitor the measured velocities, data quality, and the stability of the sampling environment. Borehole flow can be measured accurately as low as 25.9 ft/d (0.0003 ft/s), using centralizers, and to 86.4 ft/d (0.001 ft/s) without centralizers. The upper limit of velocity measurement is about 691,000 ft/d (8 ft/s). Operation of the ADV depends on user-specified velocity limits over which the system searches for the velocity signal. The closer the specified limits are to the true velocity field, the more accurate the measurement of velocity of the tracked particles in the flow field.

Colloidal Borescope

The colloidal-borescope system was developed by Oak Ridge National Laboratory (Department of Energy, 1993) and is manufactured for and distributed by AquaVISION Environmental LLC of Palisade, Colo. Colloidal-borescope services for this study were provided by RAS, Inc., of Golden, Colo., in cooperation with AquaVISION Environmental LLC. The colloidal borescope uses a video camera to view natural colloids in the ground water. As the colloids flow past the view of the camera, they are tracked and digitized by

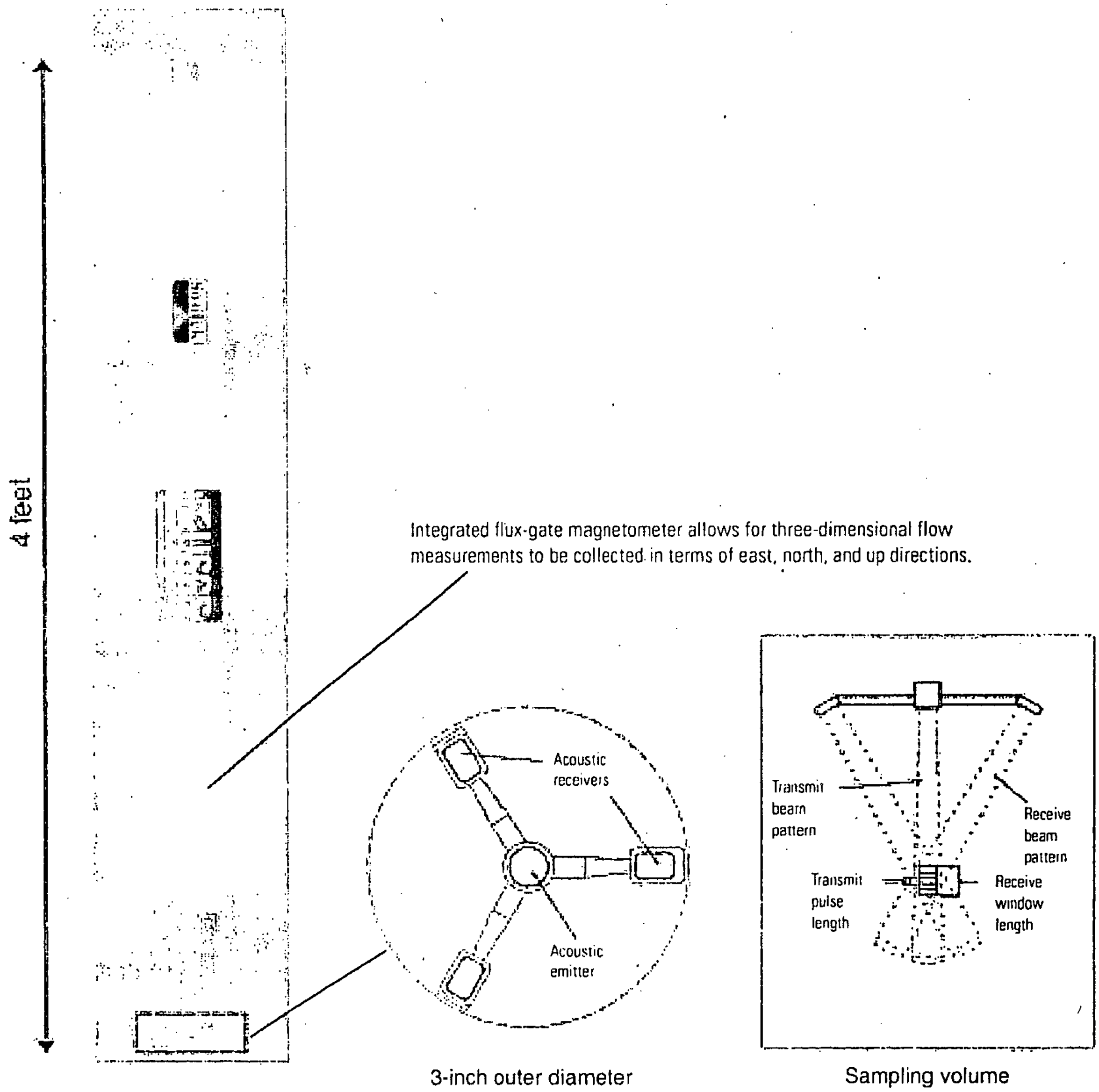


Figure 2. Borehole acoustic Doppler velocimeter (ADV) showing the configuration of the acoustic emitter and receivers on the probe tip and the sampling volume below the probe tip.

computer for speed and direction. A flux-gate magnetometer (compass) is incorporated into the system to reference flow directions to magnetic north. The colloidal borescope is attached to and powered through an underwater camera cable. The borescope is a lightweight instrument, and it can be lowered into a well by hand. A wooden clamp is fastened to the cable at the top of the casing to hold the borescope in place while measurements are made. A depth scale is incorporated with the cable, and the depth can be verified with conventional measuring tapes.

The colloidal borescope consists of a charged-couple device camera, a flux-gate magnetometer, an optical magnification lens, an illumination source, and a stainless-steel housing. The housing is approximately 24 inches long and has a diameter of 1.7 inches (fig. 3), which allows it to be used in a 2-inch-diameter monitoring well. When the colloidal borescope is in operation, an electronic image is magnified 140 times and transmitted to the surface where it is viewed and analyzed. The flux-gate magnetometer is used to determine alignment of the borescope in the well so that measurements are referenced to north.

As particles in the ground water pass beneath the lens, the backlighting source illuminates the particles, similar to a conventional microscope with a lighted stage. A video-frame grabber digitizes individual video frames at intervals selected by the operator. Computer software, developed by Oak Ridge National Laboratory, compares the two digitized video frames, matches particles from the two images, and assigns pixel addresses to the particles (Kearl and Roemer, 1998). Only particles that remain in focus across the field of view (indicating horizontal flow) are analyzed. Using this information, the software computes and records the average particle size, number of particles, speed, and direction. The system is capable of analyzing flow measurements every 4 seconds, resulting in a large data base after only a few minutes of observations. The colloidal borescope is capable of measuring velocities from essentially stagnant, zero-flow conditions to 7,085 ft/d (25 mm/s) (AquaVISION Environmental, 2000).

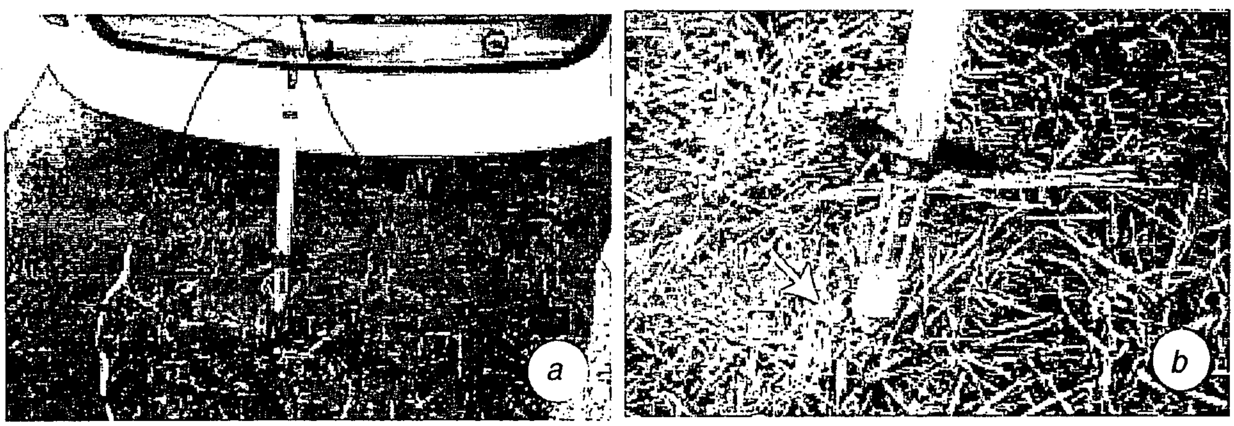


Figure 3. Photographs of (a) the collodial borescope with its power cable and (b) the camera end where colloids are viewed as water flows through the open area where the three bars connect to the base (arrow points to US quarter for scale; note rubber disc above camera to help isolate horizontal flow).

Flow velocities and directions measured by the colloidal borescope have been verified, using a sand-tank laminar-flow chamber developed at the Desert Research Institute in Boulder City, Nev. (Kearl, 1997). The sand-tank experiments also tested the colloidal borescope for measuring flow in layered sediments that included fine, medium, and coarse sand. The sand-tank experiments showed that the variability in flow direction and velocity measurements decreased with higher velocities.

For the colloidal borescope to be an effective tool in characterizing ground-water flow, it is necessary to differentiate and quantify the effects of aquifer heterogeneity, filter packs, and well skins on flow in a well bore (Kearl, 1997). This can be difficult because the hydraulic conductivity of the filter pack and surrounding formation may be unknown and/or the skin effects may not be quantified easily. Following some basic assumptions and general guidelines, however, it is possible to select reliable data sets and estimate a range of ground-water velocities. Only zones that display consistent horizontal laminar flow in a steady direction over a substantial time period should be considered. Swirling-flow zones may be the result of adjacent low-permeable sediments, skin effects, vertical-flow gradients, or nearby preferential flow zones that dominate flow in the observed zone (Kearl, 1997). Measurements in swirling-flow zones should be disregarded. If steady directional flow is observed, which is typical of a preferential flow zone, reliable measurements are possible.

At field sites, observed flow velocities exceed values based on conventional aquifer test methods, even velocities that are adjusted based on a borehole magnification factor (α of Drost and others, 1968). If theoretical work and laboratory results indicate the borescope provides reliable flow measurements within a specified range, this evidence would suggest that velocities in the well bore represent the maximum flow velocities in an aquifer. These results would further suggest that the maximum velocity and not the average linear velocity over the entire screen length dominates flow in the well bore under ambient flow conditions. Studies have shown that in no instances have velocity measurements using the colloidal borescope been less than velocities predicted by independent hydraulic information (Kearl, 1997). Based on the work presented in Kearl (1997), colloidal borescope measurements in the field should be reduced by a factor of 1 to 4 to calculate seepage velocity in the adjacent aquifer. For comparison of field measurements presented in this paper, the borescope measurements represent the flow velocities in the preferential flow zones, compared with average velocity measurements obtained by conventional methods. The colloidal borescope measures the maximum velocity in preferential flow zones in an aquifer; velocity is further accelerated by the effects of the radially convergent flow into the open borehole.

Hydrophysical Logging

Hydrophysical logging services were provided by RAS, Inc., of Golden, Colo. Hydrophysical logging involves replacing the borehole fluid with deionized water, followed by a series of temperature and fluid-electrical-conductivity (FEC) logs that profile the borehole to determine where formation water is entering and leaving (Tsang and others, 1990; Pedler and others, 1992). A time series of FEC logs can identify the locations and rates of inflow and outflow. Hydrophysical logging can identify vertical flow as well as horizontal flow; it surveys a length of the borehole, rather than providing point measurements. This attribute makes hydrophysical logging a valuable method for obtaining profiles of flow characteristics in uncased wells or in wells with long screens.

Hydrophysical logging has multiple applications. In this study, hydrophysical logging was used to identify and measure vertical and horizontal flow within the wells. The hydrophysical logging technology employed by RAS, Inc., is designed to analyze and determine

- the location of hydraulically conductive intervals within a well to a vertical resolution of one borehole diameter;

- the interval-specific rate of inflow during well pumping (in conjunction with the drawdown data, these data can be used to estimate interval-specific hydraulic conductivity and transmissivity);
- vertical and horizontal flow (inflow and outflow rates, with locations) during ambient flow conditions;
- inter-borehole hydraulic connections (vertical and horizontal flow) during cross-hole testing with more than one well; and
- actual contaminant concentrations associated with each identified conductive interval for any aqueous-phase contaminant when used in conjunction with a discrete-point fluid sampler.

The hydrophysical logging tool (probe) consists of an array of FEC and temperature sensors (fig. 4a). The tool can accommodate up to eight sensors—for this study, three sensors were used.

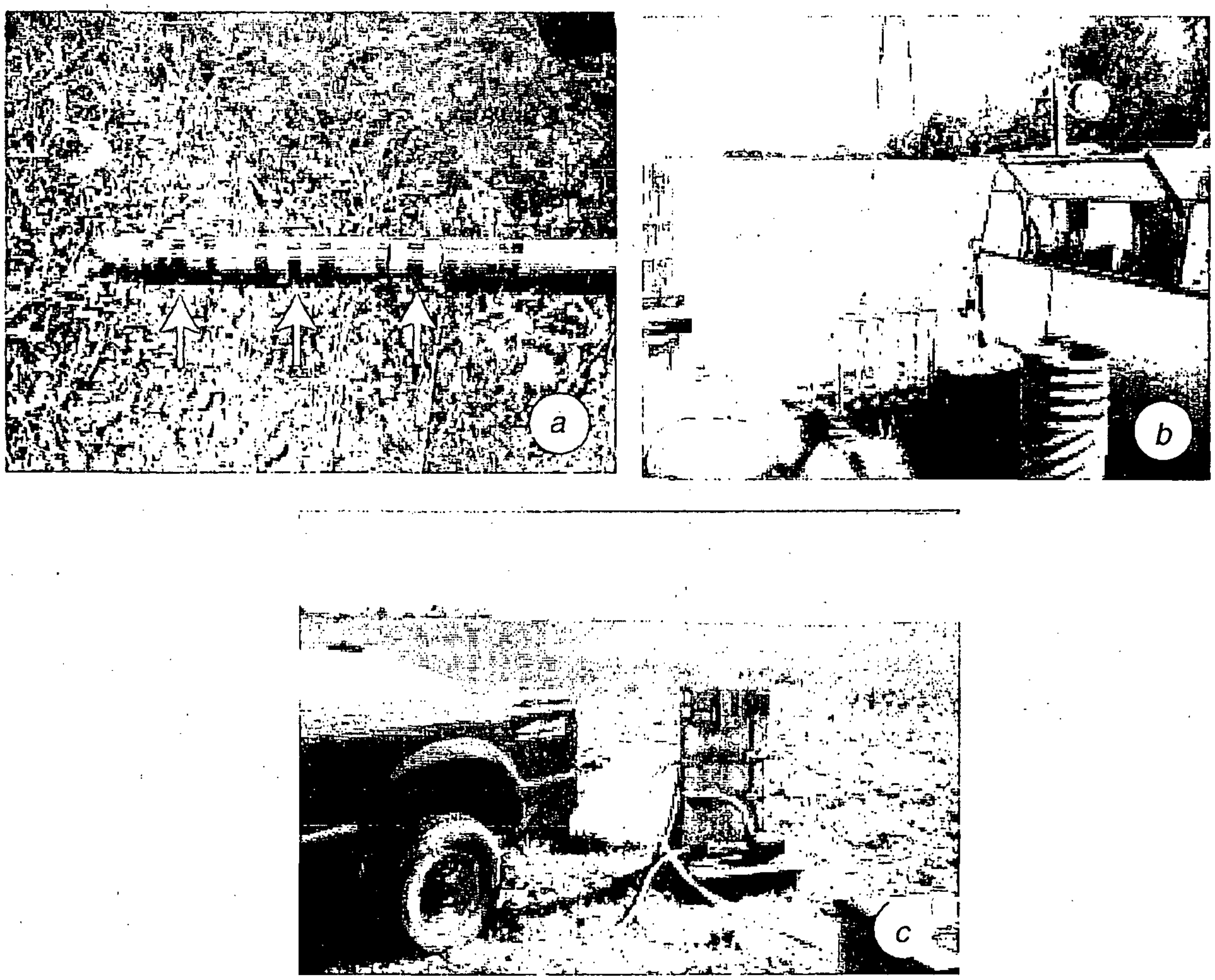


Figure 4. Photographs of (a) the fluid-electrical-conductivity and temperature sensors on the hydrophysical logging tool, (b) calibration of the tool in standpipes of water with known specific conductance and temperature, and (c) the fluid-management system for pumping water from the well and injecting deionized water from the storage tanks.

The sensors are spaced 6 inches apart and rotated at equal angles so that fluid on all sides of the tool is sampled. The hydrophysical logging tool is calibrated before each well is logged, and it is checked after each well is logged. The FEC and temperature sensors are calibrated against a range of known conductivities and temperatures (fig. 4b). A series of standpipes are used to hold the probe in standard solutions, which can be made on site using sodium chloride and deionized water. The conductivity and temperature of the different solutions in the standpipes are determined with a field meter calibrated with certified standard solutions.

The fluid-management equipment required for logging is shown in figure 4c. The fluid-management system must be capable of pumping from near the top of the water column while injecting deionized water at the bottom of the well. For this study, deionized water was produced from tap water, using portable deionization tanks. Other equipment required for hydrophysical logging includes a logging truck and the computer software for collection and analysis of the conductivity and temperature data.

The theory of hydrophysical logging is based on the law of mass balance and the linear relation between FEC and dissolved mass. By recording the changes in the electrical conductivity in the fluid column with depth, the locations of the water-producing zones can be determined and the volumetric rate of inflow can be calculated. The computer code developed for analysis of horizontal-flow rates through each zone is based largely on borehole-dilution theory in which a mixing model is used to infer horizontal ground-water-flow velocity through a borehole. The borehole-dilution technique is summarized by Freeze and Cherry (1979, p. 428) and is based on the work of Drost and others (1968). Although the theory for such analysis is well established, its application to hydrophysical logging experiments is innovative. Special considerations apply when using the theory in the fractured-rock environment; nonetheless, the theory provides promising results in such applications.

A brief explanation of borehole dilution as applied to hydrophysical logging follows. For a more detailed explanation of borehole dilution, refer to Drost and others (1968).

If a tracer (in this case, deionized water) is introduced uniformly into a section of a borehole, the concentration of the tracer C_{obs} is modified by the concentration of the formation water C_f flowing into the borehole at a velocity v^*, as illustrated in figure 5. In hydrophysical logging, FEC is substituted for concentration, so C_{obs} and C_f actually

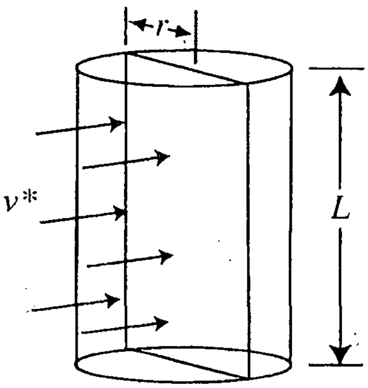


Figure 5. Schematic diagram of the borehole-dilution process showing the definitions of the geometric variables; r, the radius of the borehole; L, the length of borehole being investigated; and v^*, the velocity in the borehole.

represent observed and formation FEC values. Because the tracer is deionized water, the borehole "dilution" is actually an increase in FEC.

Balancing the net rate of mass into the borehole with the rate of change in C_{obs} yields the first-order differential equation:

$$v^*C_f A - v^*C_{obs}A = W\frac{dC_{ob}}{dt}, \tag{3}$$

where A is the cross-sectional area of the borehole ($A = 2rL$),

r is the radius of the borehole,

L is the length of the borehole, and

W is the corresponding volume.

$$W = \pi r^2 L$$

If the following change of variable is made

$$C = C_f - C_{obs}, \tag{4}$$

equation 3 can be simplified as:

$$v^*C = \frac{W}{A}\frac{dC}{dt}, \tag{5}$$

which can be solved for C:

$$C = C_0 \exp\left(-\frac{2t}{\pi r}v^*\right), \tag{6}$$

where C_0 is C at ($t = 0$) or

$$C_f - C_{obs} \text{ at } (t = 0)$$

Taking the natural logarithm of both sides of equation 6 yields

$$\ln\left(\frac{C}{C_0}\right) = -\frac{2v^*}{\pi r}t \tag{7}$$

Thus, the ratio $\frac{C}{C_0}$ should plot as a linear change with time on semi-log paper. The slope of this line is proportional to the velocity of ground water flowing through the well. Specifically,

$$v^* = \frac{\pi r \ln\left(\frac{C_2}{C_1}\right)}{2(t_2 - t_1)}, \tag{8}$$

where t_1 is the time corresponding to the value of C_1 on the straight-line segment of the semi-log plot, and

t_2 is the time corresponding to the value of C_2 on the straight-line segment of the semi-log plot.

The velocity given by equation 8 is the velocity through the borehole. The velocity through the borehole may be different from the velocity of ground water in the formation because flow lines tend to converge toward the borehole. Corrections for this convergence are given by Drost and others (1968) as

$$q = \frac{v^*}{\alpha}, \tag{9}$$

where q is the specific discharge of ground water in the aquifer, and

α is a factor that accounts for convergence of flow lines in the borehole.

In general, calculating α requires detailed knowledge of the hydraulic properties of the screen, the gravel pack (or annulus around the screen if the well is developed naturally), and the hydraulic properties of the aquifer. The value of α is relatively insensitive to the hydraulic properties, however, provided the screen and gravel pack are considerably more permeable than the aquifer. To the knowledge of the authors, these corrections have never been validated for the fractured open-hole environment. Typically, these values are calculated using a convergence factor of 2.5. In this report, only the "in borehole" velocities (v^*) have been calculated and presented in the results of the hydrophysical logging.

Description of the Study Areas and Test Wells

The borehole flowmeters were tested in wells at two army bases, Jefferson Proving Ground, Ind., (JPG) and Fort Campbell, Ky./Tenn. (FC). Using wells from the two facilities provided boreholes in different geologic settings with different diameters and contrasting types of water-bearing zones. The wells at JPG are open to bedrock consisting of layers of limestone and shaly limestone that include a water-bearing layer of limestone with apparent vuggy porosity. None of the wells at JPG intersected enlarged openings at bedding planes or fractures. The wells at Fort Campbell are open to bedrock consisting of layers of mixed carbonate lithologies with little or no intergranular porosity. Each of the wells used for flowmeter measurements at Fort Campbell intersect at least one water-bearing opening apparently widened by dissolution along bedding planes.

Jefferson Proving Ground, Indiana

JPG is near the town of Madison in southeastern Indiana and is about 6 mi north of the Ohio River. JPG is a 55,625-acre military reservation constructed by the U.S. Army between 1940 and 1941. The primary activities at JPG were production and post-production testing of conventional ammunition components and other ordnance items, as well as testing of propellant systems and components for the U.S. Army (U.S. Army Test and Evaluation Command, 2000). JPG was closed in 1995 and a process of restoration and redevelopment was begun then in preparation for transfer of some of the property to private ownership.

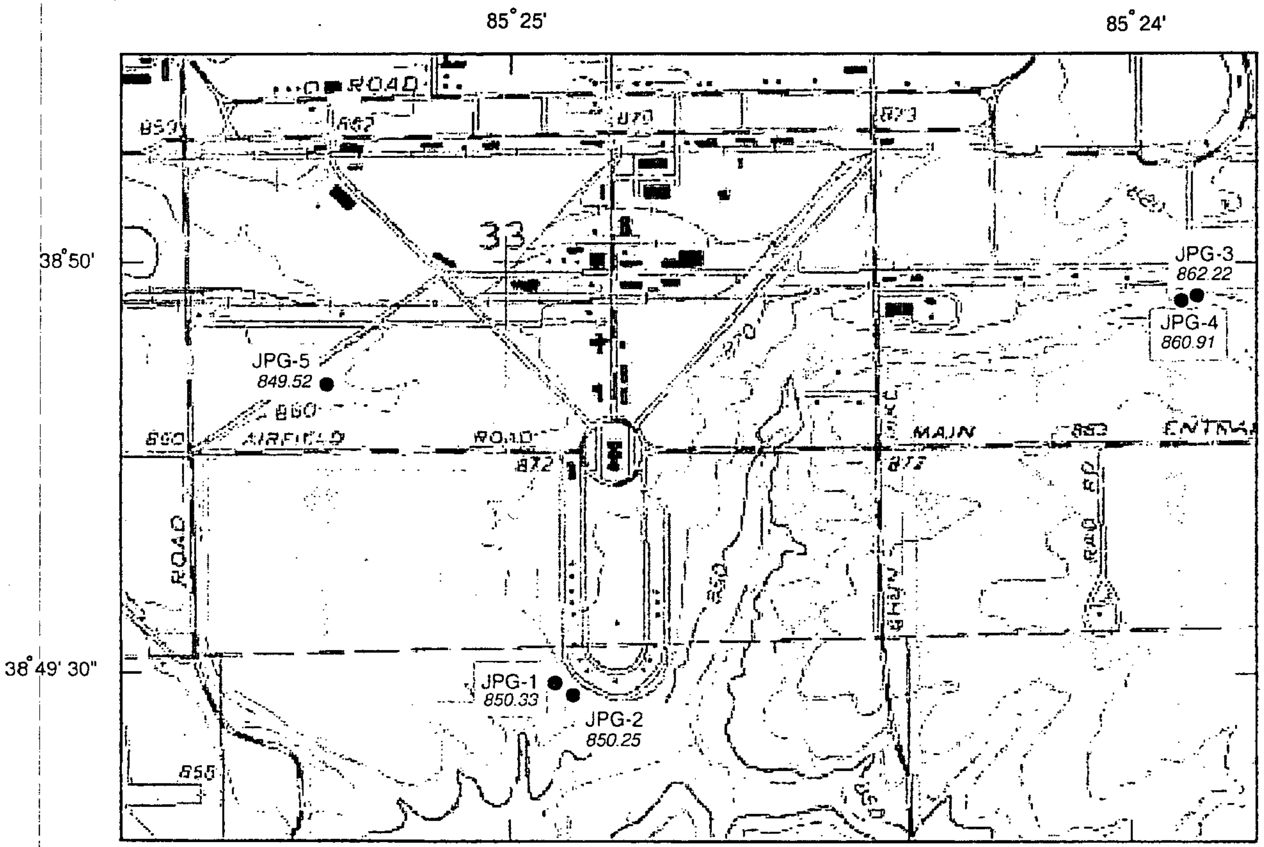
JPG is in a physiographic region known as the Muscatatuck Regional Slope, which is a gently sloping plane controlled by the westward-dipping carbonate rocks of Silurian and Devonian Age that underlie the area (Schneider, 1966). The carbonate rocks dip westward at about 20 ft/mi and are overlain by glacial drift with an average thickness of 20 to 25 ft. The drainage system is dominated by streams that flow in a south-southwest direction; to the east of the base, streams flow to the east then south to the Ohio River. The topography in the vicinity of the test wells can be characterized as a flat upland with minor drainages and gently rolling relief.

Bedrock formations beneath JPG likely include the Salamonie Dolomite and Brassfield Limestone of Silurian Age and the Whitewater and Dillsboro Formations of the Maquoketa Group of Ordovician Age (Gray, 1972; Shaver and others, 1986). The Salamonie Dolomite is characterized as argillaceous limestone, dolomitic limestone, dolomite, and shale and ranges in thickness from 0 to about 80 ft in the vicinity of JPG (Shaver and others, 1986; Greeman, 1981). The upper Salamonie Dolomite includes a coarser-grained bioclastic vuggy dolomite in much of Indiana, and chert is present sporadically in southeastern Indiana (Shaver and others, 1986). The Brassfield Limestone ranges in thickness from 0 to 20 ft and is generally a medium- to coarse-grained fossiliferous limestone with some dolomite. The Maquoketa Group is characterized as thinly layered interbedded shales and limestones, with shales increasing with depth.

The test wells at JPG are at the southern end of the base near the old headquarters, housing, and storage facilities (fig. 6). Seven wells were drilled in 1978 for the purpose of ground-water exploration in conjunction with a study of lineaments and fracture traces (Greeman, 1981). The wells were drilled to a depth of 200 ft, with a nominal diameter of 5 inches, and are cased down to bedrock with 5-inch-diameter PVC casing. In each well, most of the borehole is open to bedrock. Five wells were used to monitor water levels during this study. Borehole-flowmeter measurements were made in wells JPG-2 and JPG-5.

Fort Campbell, Kentucky/Tennessee

The Fort Campbell Military Reservation is in southwestern Kentucky and northwestern Tennessee, near the towns of Oak Grove, Ky., and Clarksville, Tenn. Fort Campbell was opened in 1942 as a training ground and is operated by the U.S. Army, 101st Airborne Division, to provide support and training for military operations. Fort



Base from U.S. Geological Survey
Digital Raster Graphics
1:24,000 Clifty Falls, 1964

0 0.5 MILE

0 0.5 KILOMETER

EXPLANATION

● JPG-1 *850.33* TEST WELL--well identifier and water-level altitude on August 24,1999. Datum is sea level

Figure 6. Location of test wells, Jefferson Proving Ground, Indiana.