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

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Conversion Factors, Vertical Datum, and Abbreviations

Multiply	By	To obtain
inch	25.4	millimeter (mm)
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
foot per mile (ft/mi)	0.1894	meter per kilometer
square mile (mi^2)	2.590	square kilometer
acre	0.4047	hectare
cubic foot (ft^3)	0.02832	cubic meter
gallon (gal)	3.785	liter
foot per second (ft/s)	0.3048	meter per second
foot per minute (ft/min)	0.3048	meter per minute
foot per day (ft/d)	0.3048	meter per day
foot per day (ft/d)	3.571×10^{-6}	meter per second
foot per day (ft/d)	3.571	micrometer per second (µm/s)
gallon per minute (gal/min)	0.0631	liter per second

Sea level: In this report, "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)—a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

Altitude, as used in this report, refers to distance above or below sea level.

Transmissivity: The standard unit for transmissivity is cubic foot per day per square foot times foot of aquifer thickness $[(ft^3/d)/ft^2]ft$. In this report, the mathematically reduced form, foot squared per day (ft^2/d), is used for convenience.

Specific conductance is given in microsiemens per centimeter at 25 degrees Celsius (µS/cm at 25°C).

Temperature in degrees Celsius (°C) can be converted to degrees Fahrenheit (°F) as follows:

$$°F = (1.8 \times °C) + 32$$

The following abbreviations are used in this report:

Abbreviation	Description
ADV	acoustic Doppler velocimeter
FC	Fort Campbell
FEC	fluid-electrical conductivity
JPG	Jefferson Proving Ground

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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 boreholes, however. Conventional borehole flowmeters, such as the vertical heat-pulse, spinner, and electromagnetic flowmeters have been used for many years to indicate the number, depth, and permeability of water-producing intervals (Schimschal, 1981; Hess, 1986; Keys, 1990; Molz and Young, 1993). Hydrophysical logging also has been used for years to identify and characterize water-producing intervals (Pedler and Urish, 1988; Pedler and others, 1992; Pedler and others, 1995). Conventional vertical flowmeters have been used to estimate the vertical profile of permeability in the borehole (Molz and others, 1989; Kabala, 1994; Hanson and Nishikawa, 1996) and to infer the presence of hydraulic head gradients adjacent to the borehole (Paillet, 1998). This information has limited value, however, because it is recognized that the borehole facilitates vertical flow between aquifers and fractures that would not normally be present. Conventional flowmeters provide no information about the velocity and direction of horizontal flow in the borehole. Hydrophysical logging can provide measurements of horizontal velocity but not of direction.

Various borehole techniques currently are being used to acquire information about horizontal ground-water flow. The USAEC, seeking the best available technologies to perform its mission, needed a description of each of these techniques. Particular interest was focused on the use of horizontal flowmeters in carbonate aquifers with bedding-plane porosity. Some army reservations are in areas with carbonate bedrock, and previous USAEC studies identified the occurrence of ground-water flow along bedding planes (Wayne Mandell, U.S. Army Environmental Center, written commun., 2000).

Two site investigations for the USAEC created the interest for this flowmeter-comparison study (Wayne Mandell, U.S. Army Environmental Center, written commun., 2000). The first study, at Beach Point, Aberdeen Proving Ground, Maryland, involved the development of a ground-water-dilution model of a dense nonaqueous phase liquid (DNAPL) plume. The solution to measuring the low flow rates in the aquifer to be modeled was to use vertical and horizontal heat-pulse flowmeters. The second study, at the Indiana Army Ammunition Plant in Charlestown, also used the vertical and horizontal heat-pulse flowmeters. The vertical flowmeter did not register vertical flow in any of the test wells. The horizontal flowmeter was used to measure horizontal ground-water flow in the test wells. A comparison of the flowmeter measurements with bedrock cores from the wells indicated that most of the ground-water flow was along bedding planes.

Purpose and Scope

This report describes, evaluates, and compares three methods of making point measurements of horizontal ground-water-flow velocity and direction in open boreholes in carbonate bedrock. This report also describes and evaluates hydrophysical logging, a fluid-conductivity logging method that can be used to measure horizontal and vertical ground-water flow (velocity and discharge) through boreholes.

Each of the three flowmeters that make point measurements uses a different technology—heat-pulse dissipation, acoustic particle tracking, and video particle tracking. Hydrophysical logging involves replacement of the borehole fluid with deionized water, followed by a series of fluid-electrical-conductivity logs to measure the locations and rates that water enters the borehole. This report describes each method's principles of operation, field techniques, advantages and disadvantages, and limitations. Data collected with each method are presented by test well and depth; where possible, comparisons are made among the methods. Results of this study provide information on the performance of the flowmeter methods in a carbonate-bedrock environment. The results of this study also may provide useful information for future investigations of borehole flowmeters.

Previous Investigations

Hydraulic properties of aquifers traditionally have been estimated from laboratory measurements of core samples or from field determinations such as slug tests or pump tests for composite sections of the aquifer. These approaches provide data that are valuable for site assessment; they may, however, undesirably average zones of preferential flow that are chief conduits of ground-water contaminants (Kearl and Case, 1992; Kearl, 1997). Similarly, horizontal-flow velocity traditionally has been estimated on the basis of Darcy's equation (using measured hydraulic gradients and conductivity) or from transport of tracers under natural or forced-gradient conditions.

Borehole tools capable of directly measuring horizontal ground-water flow and direction in narrow intervals of the aquifer provide a necessary link between the laboratory and field scale tests (Kearl, 1997). Borehole-flowmeter data indicate where ground water is entering and exiting boreholes and can assist in interpretation of contaminant transport (Kearl and others, 1994). Cross-borehole-flow logging tests can indicate the degree of connectivity of fractures beyond the well bore, and transient tests can be used to estimate hydraulic properties (for example, transmissivity and storage coefficient) of fractured aquifers (Kearl and others, 1994).

Hydraulic data for small-scale borehole features historically have been estimated from borehole-dilution and tracer tests and by use of spinner or impeller flowmeters. Borehole-dilution and tracer tests, however, generally require use of inflatable packers that are time consuming and labor intensive (Kearl and Case, 1992). Spinner and impeller flowmeters have been used widely to measure vertical flow but are somewhat limited by relatively high stall speeds that range from 2 to 10 ft/min (Hess, 1986; Keys, 1990; Crowder and others, 1994). These stall speeds equate to flows of 1.3 to 6.5 gal/min in a 4-inch-diameter well. The spinner flowmeters can be stationary or can be trolled up and down the borehole.

Heat-pulse technology allowed the development of a vertical flowmeter capable of measurements in the range of 0.2 to about 20.0 ft/min, corresponding to discharges from about 0.01 to 1.5 gal/min in a 6-inch-diameter borehole when flow diverters are used to force all flow through the small-diameter measurement section of the logging probe (Hess, 1986). Additional flowmeters that use other properties of the physical system or other technologies have been proposed. Young and others (1991) and Molz and Young (1993) describe the development and application of an electromagnetic flowmeter with a minimum threshold velocity of about 0.3 ft/min and no theoretical upper measurement limit. The minimum threshold corresponds to a discharge of about 0.02 gal/min in a 6-inch-diameter borehole when flow diverters are used to force all flow through the measurement section of the logging probe.

Heat-pulse and electromagnetic flowmeters are calibrated routinely in units of borehole discharge through the measurement section of the probe. Both measurements are made with flow diverters used to block leakage of flow in the annulus between the probe and borehole wall. Flow diversion is 100-percent effective in smooth-walled calibration tubes where probe response is calibrated in flow units. Rough-walled boreholes may allow some leakage, and calibrated flow measurements may need to be multiplied by a leakage factor. This factor usually is established in the field by comparing calibrated flowmeter response to known flow rate immediately below the pump during aquifer tests.

Drost and others (1968) developed and tested a scintillation-counter probe for the borehole environment that determined flow directions by tracing radioisotopic elements injected into the borehole.

Previous studies have documented the development and application of the colloidal borescope, hydrophysical logging, and the horizontal heat-pulse flowmeter (KVA flowmeter). Additional studies have compared the flowmeter results with information from aquifer tests and vertical flowmeter results. Because the acoustic Doppler velocimeter (ADV) recently was developed, its application has limited documentation. The technical specifications and applications of the acoustic Doppler velocimeter to surface-water measurements were introduced by Kraus and others (1994).

Hydrophysical logging also has been referred to as fluid-conductivity logging, fluid-electrical-conductivity logging, and ion logging (Cohen, 1995). Hydrophysical logging is a method of estimating the magnitude of flow on the basis of flow-induced changes of fluid conductivity in the borehole. The fluid-conductivity-logging technology originally was developed for nuclear-waste-isolation studies by the U.S. Department of Energy, and it has been modified for application in other environmental studies where the term "hydrophysical logging" was applied (Pedler and Urish, 1988; Pedler and others, 1995). Tsang and others (1990) describe the theoretical development of equations used to calculate inflow velocities and the numerical analysis of the borehole data. Assumptions and limitations of the calculations also are described in Tsang and others (1990). Hale and Tsang (1988) determined that a computer algorithm was necessary to account for dispersion in the borehole and the mixing of water from multiple inflows. Loew and others (1991) modified the numerical equations proposed by Tsang and others (1990) to include solutions for multiple interfering fractures and time-varying inflow salinities and discharges.

The KVA flowmeter (KVA Model 40 GeoFlo meter) also has been identified as the Geo Flowmeter (Guthrie, 1986). The KVA flowmeter, data collection, and calibration procedures are described by Kerfoot and others (1991). American Society for Testing and Materials (ASTM) methods have been documented for a KVA flowmeter (Kerfoot, 1995). Although a two-dimensional and three-dimensional heat-pulse flowmeter have been developed (Kerfoot, 1982), only the two-dimensional (horizontal) and one-dimensional (vertical) flowmeters are available commercially.

The colloidal borescope was developed by Oak Ridge National Laboratories. The borescope tool, application, and data analysis have been described in the literature (Kearl and Case, 1992; Kearl, 1997; Kearl and Roemer, 1998). The borescope was tested in a sand-tank laminar-flow chamber at the Desert Research Institute in Boulder City, Nev., where the controlled seepage velocities ranged from approximately 3 to 63 ft/d (Kearl, 1997). Based on that work, the borescope limitations and the corrections required for calculating actual ground-water-seepage velocity from measured flow rates were documented. The calibrated conditions—steady, horizontal, laminar flow—provide the best conditions for making measurements in the field (Kearl and others, 1999). The borescope provides a discrete-point measurement, and active flow zones can be missed depending on ground-water turbidity, thickness of the flow zone, and time spent searching for the flow zone (Korte and others, 2000).

Hydrophysical logging, the KVA flowmeter, and the colloidal borescope have been applied in a wide variety of geologic terrains. The ADV, because of its recent development, has been applied in a limited variety of settings. Applications of the flowmeters to field assessments and controlled laboratory evaluations have led to a better understanding of the distribution of ground-water flow in the borehole and the operational mechanics of the various flowmeters.

Tsang and others (1990) describe the application and validation of hydrophysical logging in a fractured crystalline bedrock aquifer. Pedler and others (1992) describe the application of hydrophysical logging to environmental investigations in shallow, fractured crystalline bedrock near two landfills in New England. Pedler and others (1992) used hydrophysical logging to examine a fractured crystalline metamorphic schist in New Hampshire where DNAPL contamination of ground water was suspected; the hydrophysical logging was used to help select locations for installing monitoring instruments. Vernon and others (1993) and Paillet and Pedler (1996) incorporated hydrophysical logging in their discussions of integrated borehole logging methods for wellhead-protection applications. Pedler and others (1995) used hydrophysical logging to investigate the ground-water transport of trichloroethylene (TCE) in a layered basalt aquifer; results indicated that water-bearing fractures appear to be continuous between closely spaced wells, but the fractured aquifer behaves more like a porous medium on a regional scale of observation. Hydrophysical logging was applied at a site specifically established to examine the hydrology of fractured rock by Cohen (1995). Because hydrophysical logging produces continuous profiles of the fluid conductivity, a major benefit of the technique is its usefulness in identifying and quantifying flow zones in deep, uncased wells or in wells with long screened intervals.

The KVA flowmeter was used to delineate the local ground-water-flow system at a landfill positioned between a stormwater-retention pond and a tidally affected intercoastal waterway where the underlying deposits consisted of highly heterogeneous, interlayered fine- and coarse-grained sediments (Guthrie, 1986).

The colloidal borescope was used to examine a heterogeneous aquifer consisting of interlayered clayey silt and sand lenses. Results indicated that multiple measurements within the same sand lens provided consistent flow rates and directions, but vectors changed within each sand lens in the aquifer at different locations in response to varying patterns of ground-water recharge and discharge (Kearl and Roemer, 1998). The colloidal borescope was used to examine the site of a leaking underground storage tank; results determined that flow directions in the unfractured bedrock intervals paralleled the regional flow gradient determined by water-level measurements, but flow in individual fractures paralleled the strike of mapped faults (Kearl and others, 1999). Flow in the fractured intervals was approximately 10 times faster than that predicted from the regional gradient, which explained the location of the contaminant plume (Kearl and others, 1999). The colloidal borescope also was used in an unconsolidated aquifer to examine the effects of well purging and sampling protocols on ground-water-quality samples (Kearl and others, 1992; Kearl and others, 1994).

Field applications and controlled laboratory studies have determined that the representativeness of borehole-flowmeter measurements is subject to several variables. The presence of the borehole itself and the tool being positioned in the borehole disturb the natural flow field (Kearl and others, 1994). The convergence of flow lines from the formation to the borehole (that has infinite permeability) may produce flow rates 1 to 4 times greater than the actual flow rate in the aquifer (Bidaux and Tsang, 1991; Momii and others, 1993; Kearl, 1997). Thermal convection, caused by inflow of fluid that has a different temperature than that of the fluid in the borehole, can cause turbulence and affect or prevent a velocity measurement (Kearl and others, 1994; Paillet and others, 1994). High ground-water-flow rates in preferential flow zones may create eddies in the borehole adjacent to zones of low permeability and produce measurements that are difficult to interpret (Kearl, 1997).

The interpretation of flow measurements can be complicated by flow regimes changing with time as measurements are being made. It is sometimes difficult to determine if a change in measured flow represents a difference in flow over the thickness of the aquifer or just a change in flow field with time (Paillet and others, 1994). The presence of the flowmeter in the borehole may produce eddies in vertically moving ground water that can affect measurements; in some cases, measured flow directions have indicated a vertical hydraulic head known to be incorrect (Kearl and others, 1994; Paillet and others, 1994). Tool insertion can cause a pressure-pulse effect from fluid displacement by the tool that, in turn, affects flow measurements (Kerfoot, 1988). A similar effect is created by pressure changes at land surface (such as surface-water fluctuations and heavy traffic) at sites where the water table is close to land surface (Kerfoot, 1988; Kearl, 1997).

The nature of the aquifer heterogeneities also can affect the ground-water-flow measurement. Flowmeter measurements are particularly sensitive to flowmeter positioning relative to the preferential flow zone (Molz and others, 1989; Kearl and others, 1994). Steeply inclined fractures also may produce results that are difficult to interpret because of nonhorizontal flow across the borehole (Kerfoot and others, 1991). The acoustic Doppler velocimeter is the only tool of the three point-measurement methods capable of measuring three-dimensional flow.

Hydrophysical logging, the KVA flowmeter, and the colloidal borescope have been used with other flowmeters or with traditional methods of measuring ground-water flow to perform site investigations. Multiple methods were used to gain more information about a study site or reinforce other findings, but direct comparison of results usually was not the intent. Evans and others (1996) used hydrophysical logging and a vertical heat-pulse flowmeter to log three wells in a fractured gneiss under pumped and ambient-flow conditions.

Both methods identified fractures at the same locations and, when combined with drawdown data, indicated comparable values of transmissivity.

Hydrophysical logging and the vertical heat-pulse flowmeter were used with dye tracing and traditional borehole and surface geophysical measurements in fractured bedrock consisting of schist and metasedimentary rocks intruded by quartz monzonite (Vernon and others, 1993). The results were used to define a conceptual aquifer model, estimate optimum locations for monitoring wells, and define a wellhead-protection area. Results from the hydrophysical logging and vertical heat-pulse flowmeter generally were comparable, but the hydrophysical logging was able to identify additional inflow-outflow zones that had very low discharges. Hydrophysical logging was used to evaluate the conductivity and temperature of water flowing from each individual fracture, and it was capable of detecting low-conductivity water. Low-conductivity water can be indicative of meteoric water, which is relevant to wellhead-protection studies. Loew and others (1991) used fluid-conductivity methods in the Leuggern deep well of northern Switzerland. Results of the fluid-conductivity logging compared favorably with transmissivity values based on aquifer tests using packers. Hydrophysical logging was used with several traditional techniques and a vertical heat-pulse flowmeter to develop a hydrogeologic characterization of a fractured-rock formation in the foothills of the central Sierra Nevada in California (Cohen, 1995).

The KVA flowmeter was used with slow-release dyes to determine ground-water flow in bedrock for wellhead protection (Kerfoot, 1992). Kerfoot (1995) summarized four case studies where the application of the KVA flowmeter at Superfund sites was verified by long-term observations and tracer tests.

The colloidal borescope was tested at two sites with unconsolidated aquifers to determine comparability with conventional methods of determining ground-water-flow rates (Kearl and Case, 1992). Results of the study showed that the colloidal borescope measured velocities at least 10 times greater than the conventional methods. The velocities were interpreted as representing discharges through preferential flow zones rather than the average linear velocity. A calibration constant was determined to relate the borehole velocity to the average linear velocity. Measurements by other methods (including aquifer tests by bailing and pumping, wave propagation, GeoFlo meter, borehole-dilution and tracer tests) varied by 1 to 3 orders of magnitude. The colloidal borescope was used with slug tests, aquifer tests, and tracer tests at a site underlain by unconsolidated lacustrine deposits (Korte and others, 2000). The borescope identified preferential flow zones having discharges in general agreement with tracer observations but about 10 times greater than those indicated by the aquifer tests.

Summary documents have provided general comparisons of borehole flowmeters and flow-measuring methods, including some tools not described in this paper. Crowder and others (1994) documented the strengths, limitations, and fundamental development of methods used to measure borehole flow, including hydrophysical logging, fotometric logging, spinners/impellers, electromagnetics, acoustic Doppler, laser Doppler, and acoustic scattering.

It has been suggested that multiple methods of measuring flow are desirable to constrain the range of possible flow directions and velocities largely because of the uncertainty of the effect of the borehole on the flow field. Wheatcraft and Winterberg (1985) indicated that flowmeters do not accurately portray the ground-water-seepage velocities in the aquifer unless a correction mechanism is applied. The magnitude of the correction depends on the difference between the permeabilities of the well and the formation (Wheatcraft and Winterberg, 1985). Drost and others (1968) examined the effects of well screen, aquifer, and gravel-pack conductivities on the flow field by use of tracers in a laboratory "sandbox." The effect of well construction (including well screen, annular seal, drilling method, screen centralizing) on a flow field in unconsolidated deposits also was discussed by Kerfoot (1988). Results of the study determined that more screen slots, increased slot size, a uniform sand pack, and a screen centralized in the borehole can improve the representativeness of the flowmeter measurement.

Shapiro and others (1999) indicate that it is unlikely that a single method of measuring ground-water flow will be accurate in a heterogeneous aquifer. As a result, a systematic or hierarchical approach that is combined with iterative data collection may provide the best characterization of the subsurface. Integration of multiple flowmeters allows measurements at various scales and refinement of the results (Paillet and Pedler, 1996). Much of the literature has incorporated flowmeters with other borehole geophysical methods or hydraulic tests to characterize the hydrogeologic framework of study sites (Vernon and others, 1993; Hanson and Nishikawa, 1996; Paillet and Pedler, 1996; Cohen, 1995). Flowmeters (vertical or horizontal) provide direct measurements of flow that help with interpretations of hydrogeologic settings and estimates of hydraulic properties. Typically, flowmeter measurements alone cannot delineate the hydrogeologic framework, especially in deep, uncased bedrock wells.

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Description of the Flowmeters

Three borehole flowmeters and hydrophysical logging were evaluated for their capability to measure horizontal ground-water flow in carbonate bedrock. The flowmeters make point measurements of flow velocity and direction, whereas hydrophysical logging provides flow measurements estimated from measured changes in the fluid-electrical conductivity along the length of the borehole. The flowmeters are described in the order that they were used in the field, and a description of hydrophysical logging follows.

Horizontal Heat-Pulse Flowmeter

The horizontal heat-pulse (or thermal-pulse) flowmeter used for this study is manufactured by K-V Associates, Inc., of Mashpee, Mass., and is referred to as the KVA flowmeter. A description of KVA flowmeters, their uses, methods, and calibration were presented by Kerfoot (1982 and 1988). The KVA flowmeter (KVA Model 40 GeoFlo meter) uses a heat-pulse-generating and temperature-sensing system to measure the direction and velocity of horizontal ground-water flow. A pulse of heat is generated within ground water in the borehole, and temperature sensors (thermistors) positioned around the heat source monitor the heat (thermal) transmission through silica (glass) beads as affected by ground-water movement through them. The thermistors that measure the largest change in temperature after generation of the heat pulse are considered to be on or near the axis of the direction of ground-water flow. Thermistor machine-unit values correspond to ground-water-flow velocities and are related to the rate at which temperature changes are convected by ground-water flow across the thermistor array.

The KVA flowmeter is operated in the field by inserting the probe into a borehole at the selected depth. The probe is operated electrically by a control panel (fig. 1). The flowmeter is attached to lightweight aluminum rods used to move the probe up and down the well and determine depth. The end of the probe is threaded into a porous shroud or "fuzzy packer" filled with glass beads that surround the heat source and thermistors (fig. 1). Once the probe is inserted into a well, ground water saturates the pore space between the glass beads so that the heat source and thermistors are surrounded by ground water and glass beads and are hydraulically connected to the borehole wall or screen by the fuzzy packer. The fuzzy packer is constructed of a section of PVC (polyvinyl chloride) pipe with many uniformly spaced holes. A screen covers the sides and bottom; plastic polymer pile is attached to the outside of the screen and exterior side walls; uniform-sized glass beads of known porosity and hydraulic conductivity fill the interior. Measurements of ground-water flow are taken in a controlled environment where ground water flows from the external media through the fuzzy packer back to the external media. The top of the fuzzy packer, where the probe is attached, is solid PVC that blocks vertical flow through the probe as long as the fuzzy packer fits snugly against the borehole wall.

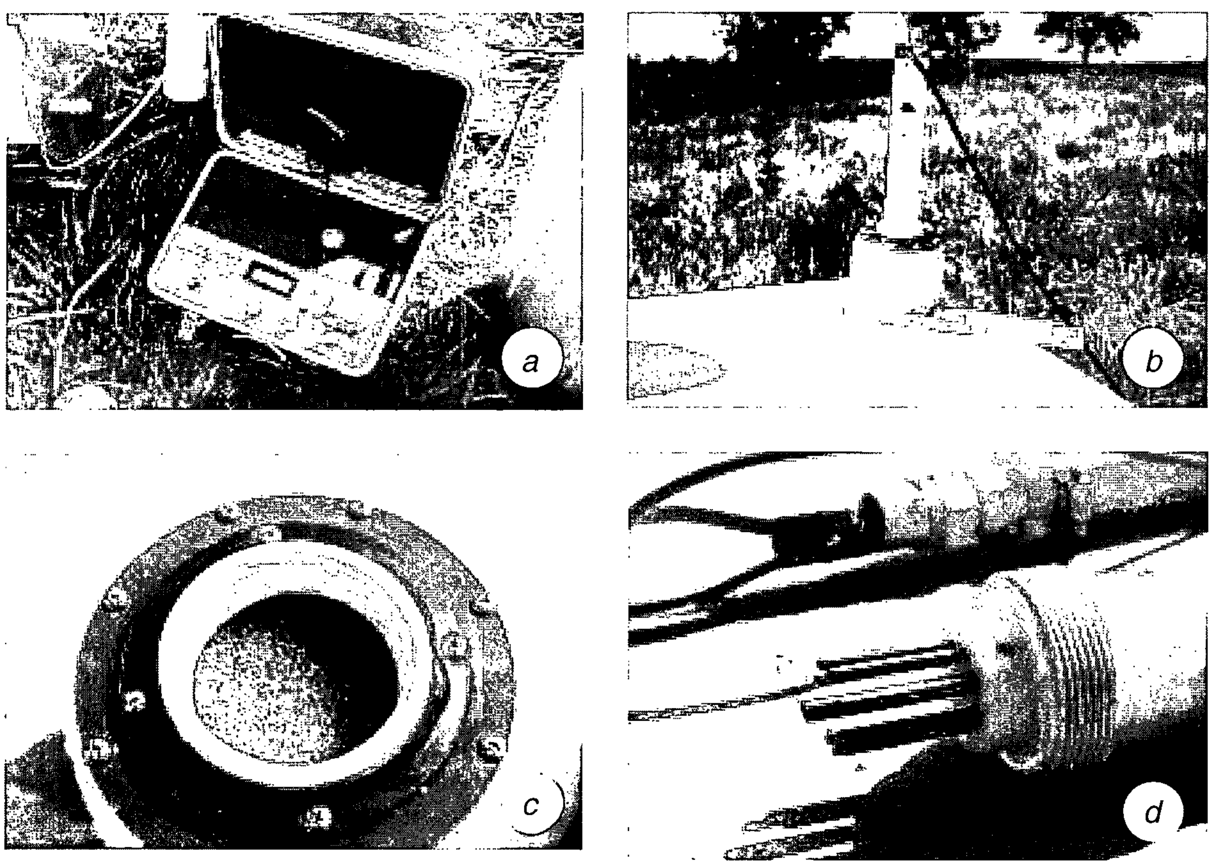


Figure 1. Photographs of (a) the KVA flowmeter control panel, (b) the KVA flowmeter attached to a fuzzy packer, (c) uniform-sized glass beads inside the fuzzy packer, and (d) the probe tip with heat source and surrounding thermistors.

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

$$f = (2K_r)/(1 + K_r), \qquad (1)$$

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

$$K_r = \frac{K_{i+a}}{K_o}, \qquad (2)$$

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

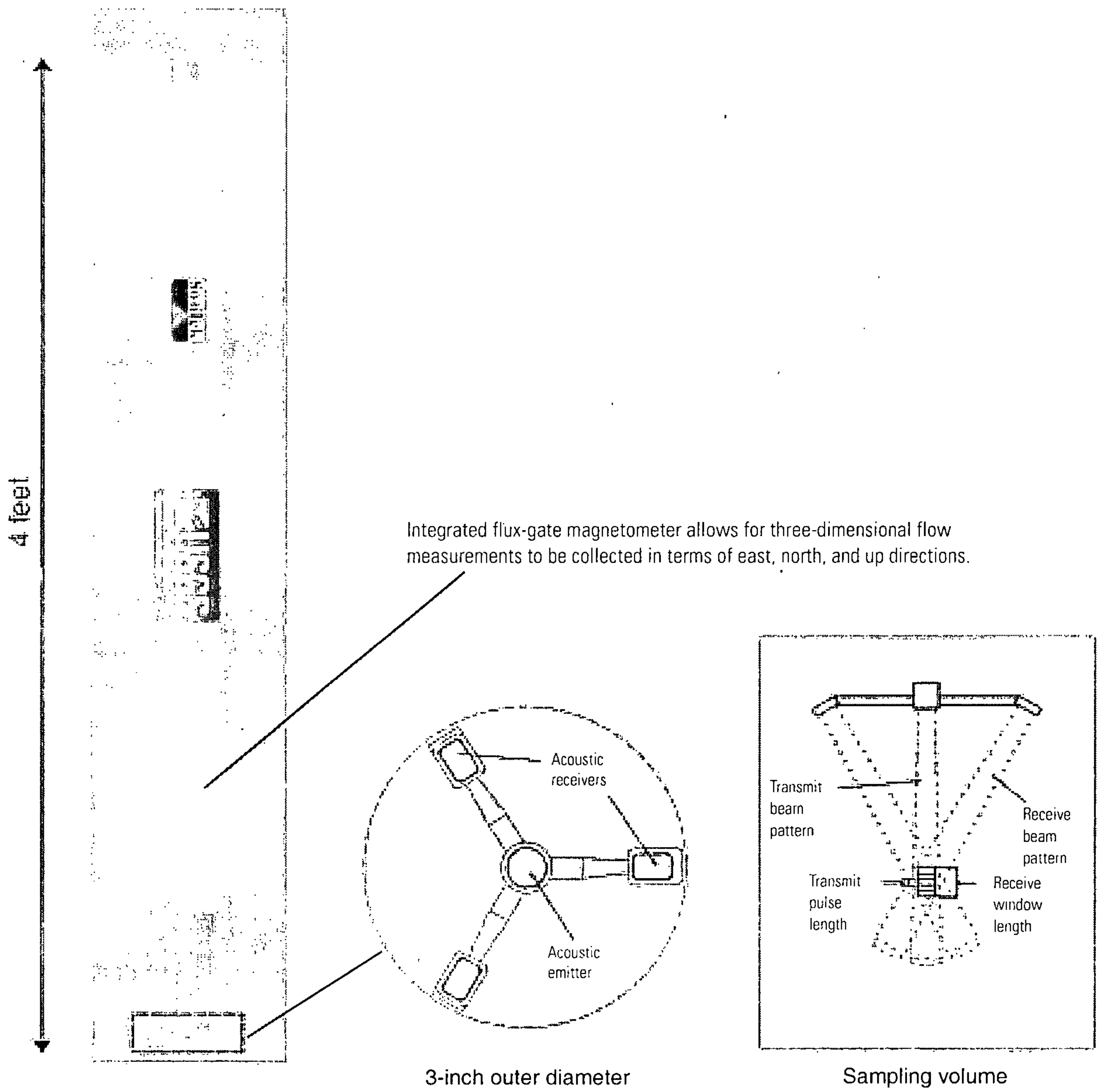


Figure 2. Borehole acoustic Doppler velocimeter (ADV) showing the configuration of the acoustic emitter and receivers on the probe tip and the sampling volume below the probe tip.

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).

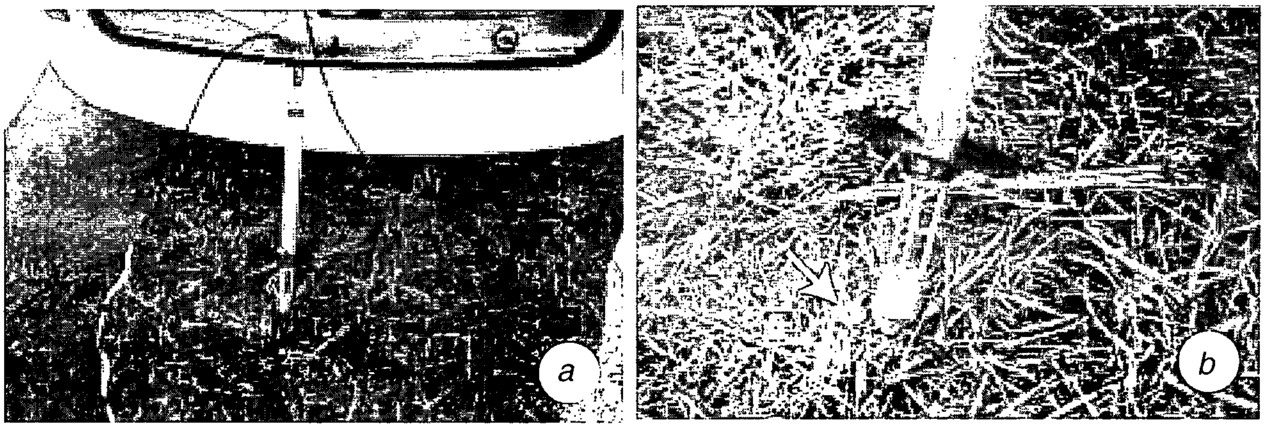


Figure 3. Photographs of (a) the collodial borescope with its power cable and (b) the camera end where colloids are viewed as water flows through the open area where the three bars connect to the base (arrow points to US quarter for scale; note rubber disc above camera to help isolate horizontal flow).

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.

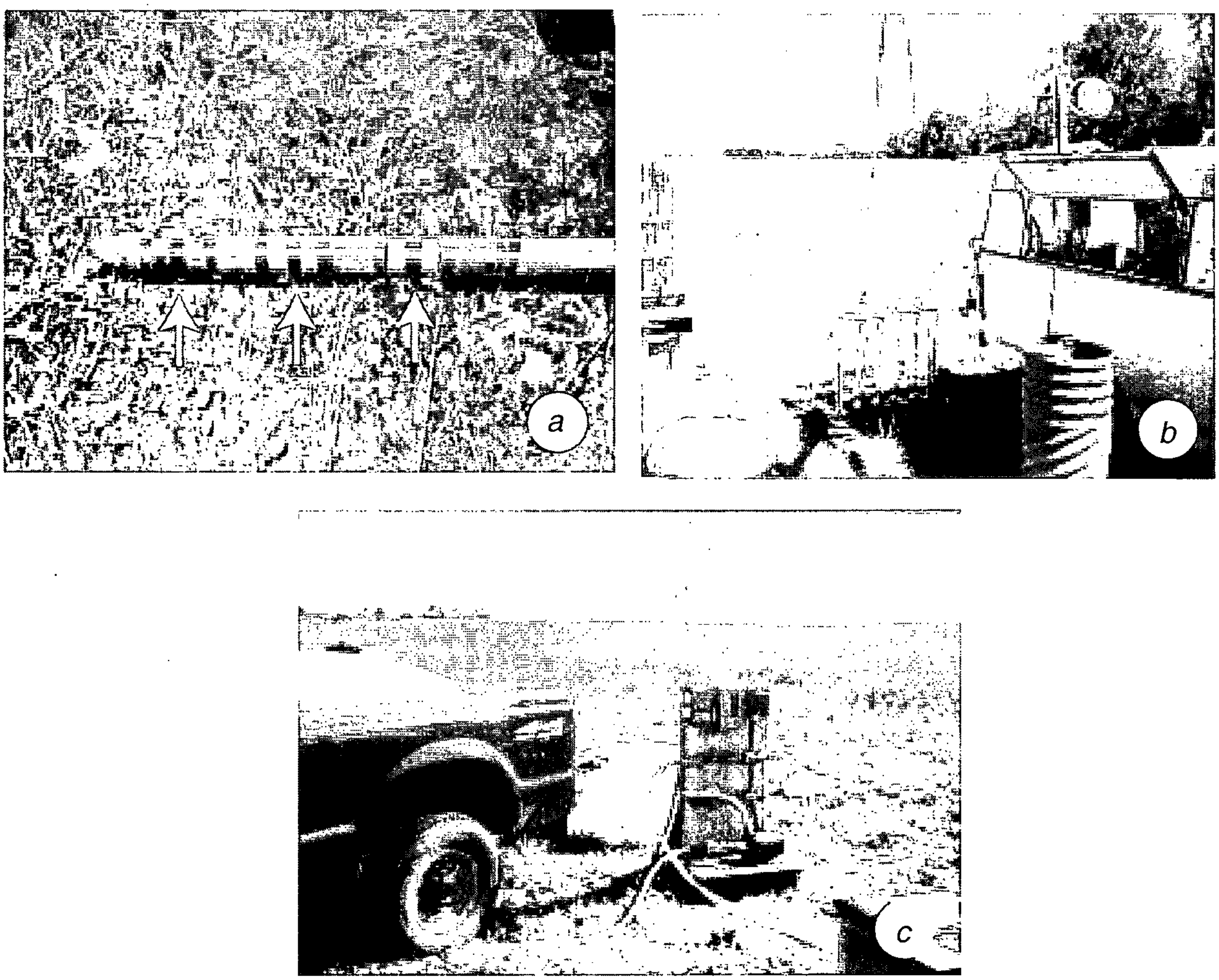


Figure 4. Photographs of (a) the fluid-electrical-conductivity and temperature sensors on the hydrophysical logging tool, (b) calibration of the tool in standpipes of water with known specific conductance and temperature, and (c) the fluid-management system for pumping water from the well and injecting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

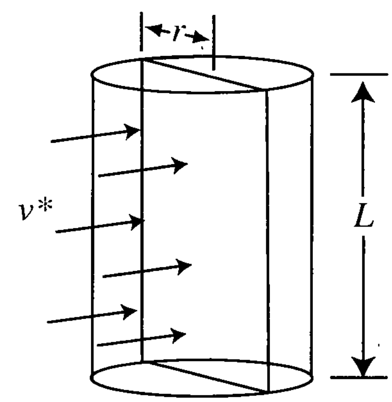


Figure 5. Schematic diagram of the borehole-dilution process showing the definitions of the geometric variables; *r*, the radius of the borehole; *L*, the length of borehole being investigated; and v^*, the velocity in the borehole.

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:

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

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

$$C = C_f - C_{obs}, \qquad (4)$$

equation 3 can be simplified as:

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

which can be solved for C:

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

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

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

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,

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

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

$$q = \frac{v^*}{\alpha}, \qquad (9)$$

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.

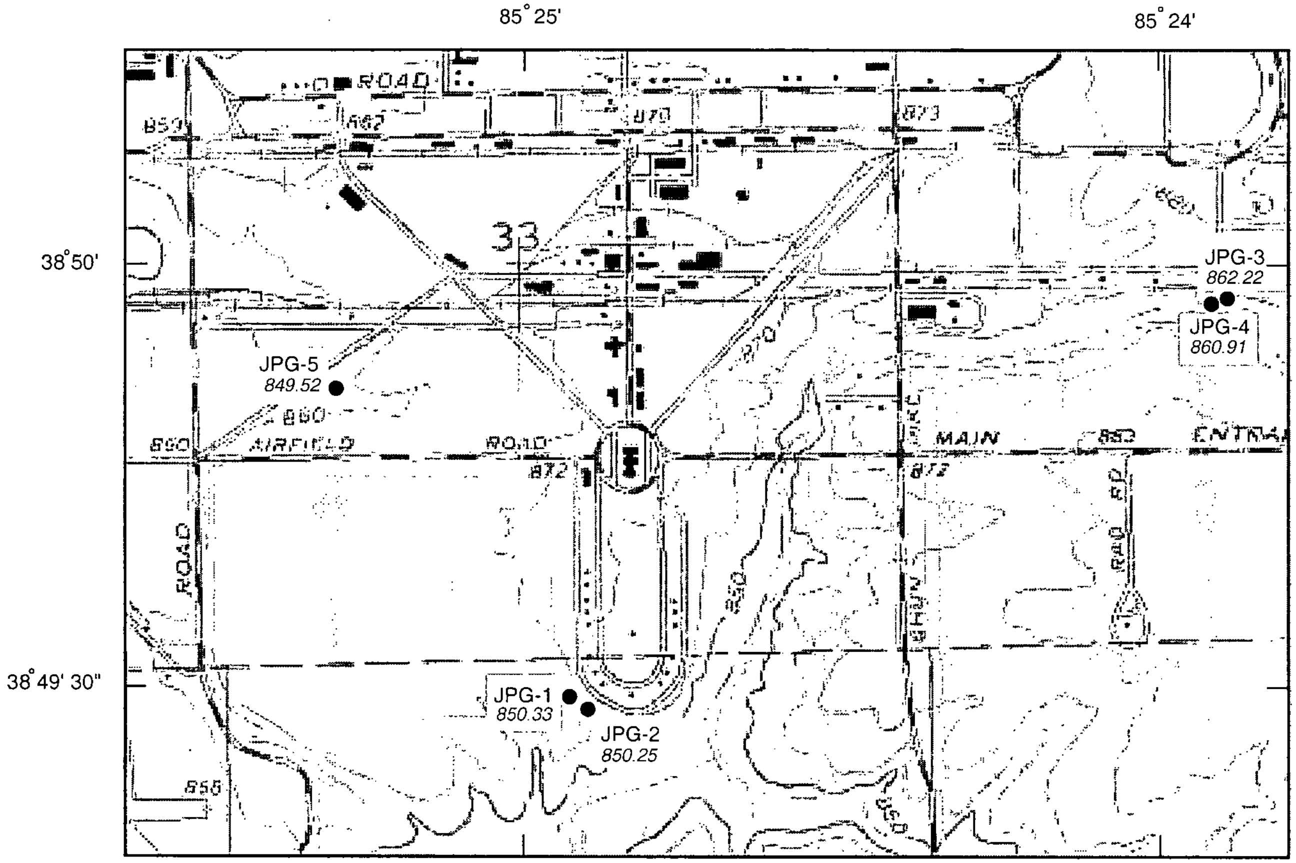
JPG is in a physiographic region known as the Muscatatuck Regional Slope, which is a gently sloping plane controlled by the westward-dipping carbonate rocks of Silurian and Devonian Age that underlie the area (Schneider, 1966). The carbonate rocks dip westward at about 20 ft/mi and are overlain by glacial 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

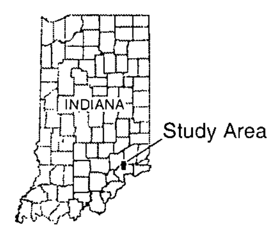


Figure 6. Location of test wells, Jefferson Proving Ground, Indiana.

Campbell occupies 105,068 acres, two-thirds of which are in Tennessee (U.S. Army, 2000). About 93,000 acres of the base are dedicated to training grounds and firing ranges. The test wells for this study are in the eastern part of the training area.

Fort Campbell lies within the western Highland Rim physiographic region of Tennessee (Miller, 1974) and the southern part of the Mississippian Plateau/Pennyrile Region of Kentucky (Kentucky Geological Survey, 2000). Prominent karst features on the base include sinkholes, caves, springs, and disappearing streams (Ank Webbers, U.S. Geological Survey, written commun., 1996). Topography in the vicinity of the study wells is characterized as low rolling hills with land uses that include forest, cropland, and firing ranges. Noahs Spring Branch flows to the east-southeast and occupies a deeply incised stream valley through the study area (fig. 7).

The bedrock geology of the area consists primarily of massive Mississippian-Age carbonate formations that include the Ste. Genevieve Limestone, the St. Louis Limestone, and the Warsaw Limestone. These three formations consist primarily of limestone with interbedded siliceous, argillaceous, oolitic, or dolomitic zones (Wilson, 1986; Klemic, 1966). The massive carbonate bedrock is overlain by varying thicknesses of regolith, which is the unconsolidated weathered residuum of the bedrock.

The test wells at Fort Campbell were selected from wells installed in 1994 as part of a hydrologic investigation of the base (Ank Webbers, U.S. Geological Survey, written commun., 1996). Six of the wells were used to monitor water levels during this study (fig. 7). Borehole-flowmeter measurements were made in wells FC-15, FC-16, and FC-29. These wells were drilled to a depth of 161 ft, with a nominal borehole diameter of 6 inches. The wells are cased to bedrock with 6.25-inch-diameter steel casing. The length of borehole open to bedrock varies with each well and ranges from 73 ft to 119 ft. Several cavities in the bedrock were encountered during the drilling of the wells (Ank Webbers, U.S. Geological Survey, written commun., 1996). Wells FC-15, FC-16, and FC-29 each intersect at least one water-bearing opening, apparently widened by dissolution along bedding planes.

Methods of Investigation

This study of horizontal flowmeters began with the selection of test wells. Test wells were selected from JPG and Fort Campbell because those sites had existing wells open to bedrock and they were U.S. Army facilities accessible to the USAEC and the USGS. Background geophysical logging and vertical-flow logging were done in each of the wells to identify potential measuring zones. Arrangements were made so that each of the horizontal-flowmeter techniques was completed by contractors with extensive experience in the application and, in some cases, the development of the technology. Each contractor made measurements at specified depths in the test wells. The specified depths were selected on the basis of background geophysical logs provided by the USGS and a borehole camera provided by K-V Associates, Inc., the contractor on site first. Well JPG-2 was tested twice, once under ambient conditions and once while pumping a nearby well 150 ft away. Contractors were on site at different times during an approximately 1-month period. Each contractor independently analyzed the data for his respective technique. The results of each contractor's measurements were provided to the USGS for compilation in this report.

Background Geophysical Logging

Background geophysical logging of the test wells was completed by the USGS in June 1999. The logging was done to characterize the general geological and hydrological conditions for each of the test wells. This preliminary work was considered to be critical for the effective testing of horizontal flowmeters because of the need to identify permeable beds, fractures, and solution openings associated with flow within the test wells. The distribution of permeability in carbonate aquifers can be variable, and the variations in permeability can cause local variations in the

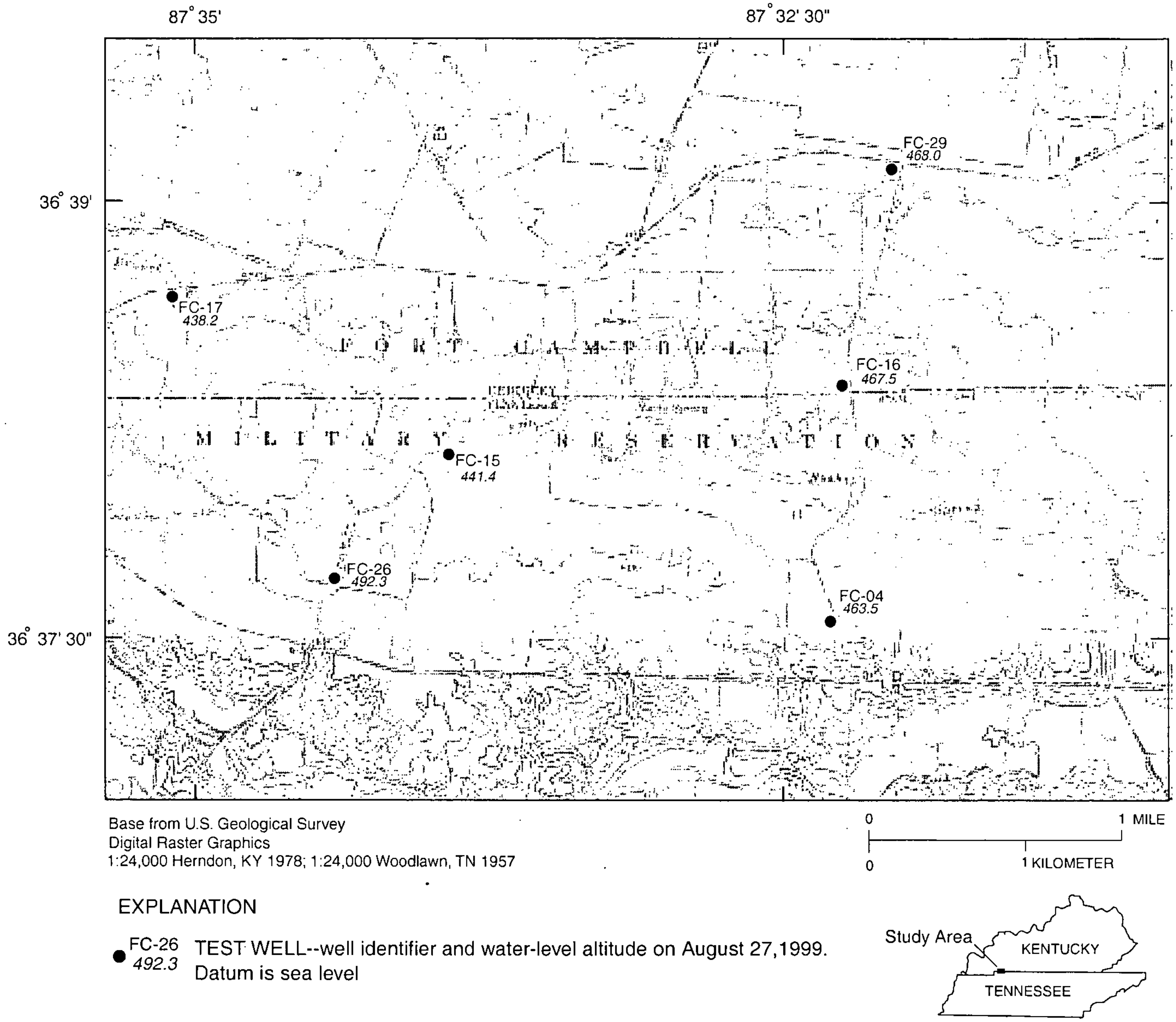


Figure 7. Location of test wells, Fort Campbell, Kentucky/Tennessee.

ground-water-flow distribution. This variability is compounded further by the effect of the borehole on the flow field. Because of time constraints, some of the intended horizontal-flow measurements could be performed only at a limited number of depth intervals, so it was important to define the intervals where flow measurements would apply to aquifers of interest. For these reasons, the primary objectives of the background characterization were 1) to identify depth intervals where horizontal-flow measurements were likely to be meaningful and 2) to identify landmarks such as beds, bedding planes, and fractures that could be identified consistently with differing depth-measurement systems subject to various amounts of cable-stretch or other depth-measurement errors.

The suite of geophysical well logs used to characterize the geologic and hydrologic conditions of each of the test wells were gamma, long- and short-normal resistivity, neutron porosity, caliper, and acoustic televiewer. A brief explanation of the function and interpretation of each of these logs is provided here; for more detailed information, refer to Keys (1990), Paillet and others (1994), and Hearst and others (2000).

- **Gamma log.** The gamma log measures the relative natural gamma activity of formations, measuring the average emission rate of gamma rays from the naturally occurring isotopes of potassium, uranium, and thorium. The gamma-count rate usually is assumed to be proportional to the fraction of fine-grained clay minerals present in a formation because these natural radioisotopes often are present in clays or shales and usually are absent from quartz sand, limestone, and dolomite. The gamma log gives a qualitative indication of the lithology, expressed as the relative amount of fine-grained minerals (clay or shale) present in the formation.
- **Normal-resistivity log**. The long- and short-normal resistivity logs measure the specific (electrical) resistivity of the formation adjacent to the borehole. The short-normal log has an electrode spacing that causes the short-normal response to provide somewhat better depth resolution than that given by the long normal. The normal logs were used instead of the induction log because the normal-resistivity measurement is considered to be more effective than the induction-log measurement in resistive rocks such as limestone and dolomite saturated by fresh water. In this study, the variations in formation resistivity also are considered to indicate the relative abundance of electrically conductive clay minerals. The short-normal log is used in combination with the gamma log as an indicator of lithology.
- **Neutron-porosity log**. The neutron log measures the rate at which neutrons from a downhole source are scattered back from the formation to a detector located a fixed distance uphole from the source. Because the neutron measurement is sensitive to the water in the borehole as well as to the fluid-filled porosity in the formation, measurements are made at two different source-to-detector spacings. The dual-detector measurement renders the neutron log less sensitive to the fluid column than does a single-detector measurement. The measured neutron-detector responses, in counts per minute, are calibrated in terms of fluid-filled porosity in percent. The calibrated neutron-log response, however, gives total porosity, including effective porosity of pore spaces and the noneffective porosity of water bound within clay minerals.
- **Caliper log.** The caliper log is a mechanical device that uses three spring-loaded arms to measure borehole diameter. The caliper log records the average deflection of the three arms. Because of the finite length of the caliper arms and the finite diameter of the tips on the arms, the caliper log can resolve the vertical thickness of bedding-plane openings and fractures to within a fraction of a foot (about 2 inches). There also is mechanical hysteresis in the caliper system; small differences in caliper output can result when the arms are extended and returned to exactly the same position. Therefore, the caliper is an effective indicator of relative changes in borehole diameter, but the cali-

brated values given by the log may be in error by as much as 0.25 inch.

- **Acoustic televiewer.** The televiewer produces an image of the borehole wall by recording the pattern of the intensity of an acoustic pulse reflected from the borehole wall. Smooth, hard sections of borehole wall provide a uniform pattern of high reflective energy. Bedding planes and fractures scatter acoustic energy, and they appear as linear features characterized by low reflectivity. The televiewer image can resolve features as small as 0.05 inch. Televiewer-log images are generated with so much detail that they are difficult to compress to a scale comparable to that of other logs. This study used televiewer-log-interpretation plots for correlation with other logs.

Although geophysical logs can provide a useful quantitative indicator of the lithologic column, geophysical measurements do not provide direct information about hydrogeology. At best, hydraulic properties of formations adjacent to boreholes are estimated, using complicated interpretation equations such as empirical regressions of porosity and permeability. Conventional borehole-flowmeter logs measuring the vertical distribution of flow are used to give a more direct estimate of formation permeability (Hill, 1990). Recent high-resolution flow-logging equipment such as the heat-pulse (Hess, 1986) and electromagnetic (Molz and others, 1994) flowmeters improve the capability to profile flow in boreholes. Under the assumption that there is no vertical hydraulic head gradient near the borehole (Molz and others, 1989), the relative transmissivity of each producing zone is given as proportional to the amount of inflow from that zone during pumping. In the more common case of vertical head gradients, the inflow depends on the product of head difference driving the flow and zone transmissivity. Paillet (1998, 2000) shows that flow profiles obtained under two different quasi-steady conditions (usually ambient and pumped conditions) can be solved explicitly for the hydraulic head and transmissivity in each zone. This analysis was completed for each of the test wells used in this study. Flow profiles were made, using the vertical heat-pulse flowmeter under ambient conditions and under steady pumping at about 1 gal/min. The pairs of profiles obtained under the two conditions were used to identify the water-producing zones and to provide estimates of zone hydraulic head and transmissivity. The transmissivity estimates were used, in turn, to estimate zone permeability, based on estimates of zone thickness from the other geophysical logs.

The permeability resolution imposed by the open-borehole environment is an important limitation on the analysis of vertical-flow profiles to estimate formation transmissivity. Variations in borehole diameter introduce scatter into the flow measurements. The scatter is usually large enough that relatively small inflows cannot be identified within the scatter. Paillet (1998) shows that the open-borehole-measurement scatter effectively imposes a 1.5 order of magnitude range on the analysis. That is, flow in water-producing zones with transmissivities of about 2 orders of magnitude smaller than that of the most productive zone will not be measured consistently. Because the method gives estimates of transmissivity and not of permeability, a thin zone of relatively high permeability might be overlooked. This limitation was not considered important for the flowmeter tests described in this report. The objective was to define permeable zones where horizontal flow would be measurable. Identification of the most transmissive zones in each test well clearly was sufficient to indicate representative depths where horizontal flow was most likely to be measured.

Vertical-flow logs can be developed from the point measurements. These vertical-flow logs then can be used to model the permeability of the water-producing zones in each borehole (Paillet, 1998). The results of the vertical-flow-log analyses giving depth, thickness, transmissivity, and relative hydraulic head for the water-producing zones in each borehole are listed in table 1. The depth to the bottom of casing for each of the wells also is listed in table 1. The vertical-flow interpretations are based on hydraulic conditions in June 1999 and might change with the seasons if the hydrologic conditions are different. The vertical flowmeter was used with centralizers to keep it in the center of

Table 1. Results of vertical-flow-log analyses for selected wells at Jefferson Proving Ground, Indiana, and Fort Campbell, Kentucky/Tennessee, June 1999

[Depths and water levels are referenced to top of casing; ft, foot; ft^2/d, foot squared per day]

Test well	Producing zone	Depth of producing zone (ft)	Thickness of producing zone (ft)	Transmissivity (ft^2/d)	Relative head[a] (ft)	Water level below top of casing (ft)	Depth to bottom of casing (ft)
			Jefferson Proving Ground				
JPG-1	1	50.0–70.0	20	7	0	15.77	39.0
JPG-2	1	45.0–65.0	20	9	0	14.88	38.3
JPG-5	1	40.0–55.0	15	12	0	10.09	34.6
			Fort Campbell				
FC-15	1	127.5–128.5	1	42	2.50	82.70	88.3
FC-15	2	142.5–143.5	1	42	0	85.20	
FC-15	3	154.0–154.5	.5	85	1.40	83.80	
FC-16	1	80.0–81.0	1	10	0	53.63	47.2
FC-29	1	66.5–68.5	2	700	.50	35.52	44.0
FC-29	2	90.5–92.5	2	70	0	36.02	

[a]Relative head is the relative difference in head between the different water-producing fractures that intersect the borehole. Vertical flow in the borehole will be from the zone of relatively higher head to the zone of lower head.

the boreholes and with a deformable disk skirt to divert the flow through the cylindrical measuring section of the probe. The vertical heat-pulse flowmeter has a flow-measuring range of 0.197 to 19.67 ft/min and can measure velocity differences as small as 0.033 ft/min (Hess, 1986). Corresponding discharges for the velocities vary with the diameter of the borehole. For example, in a 6-inch-diameter borehole, the vertical heat-pulse flowmeter has a measuring range of about 0.01 gal/min to 2.0 gal/min.

Jefferson Proving Ground, Indiana

Three wells—JPG-1, JPG-2, and JPG-5—were logged at the JPG site (figs. 8–10). Gamma, normal-resistivity, caliper, and televiewer logs were run in each of the wells. The neutron log was run only in well JPG-2 because of constraints on the use of nuclear sources and because the neutron log was used to characterize primary and not secondary porosity. Estimates of primary porosity within laterally continuous strata in well JPG-2 were assumed to apply to those same strata for the other test wells at the JPG site. Vertical-flow logs were run in each of the test wells under ambient and pumping conditions. Although none of the horizontal flowmeters were tested in well JPG-1, log data for well JPG-1 are shown (fig. 8) because pumping in well JPG-1 was used to stimulate flow between well JPG-1 and well JPG-2 where horizontal flowmeters were tested.

The logs show that the hydrogeologic conditions in each JPG test well were similar. The gamma and resistivity logs indicate an interval from just below the bottom of the casing (for example, from 52 to 75 ft in well JPG-2, fig. 9) of almost completely clay-free dolomite, with shaly dolomite below that depth. Gamma and short-normal-resistivity logs indicate that the clay mineral content generally increases with depth.

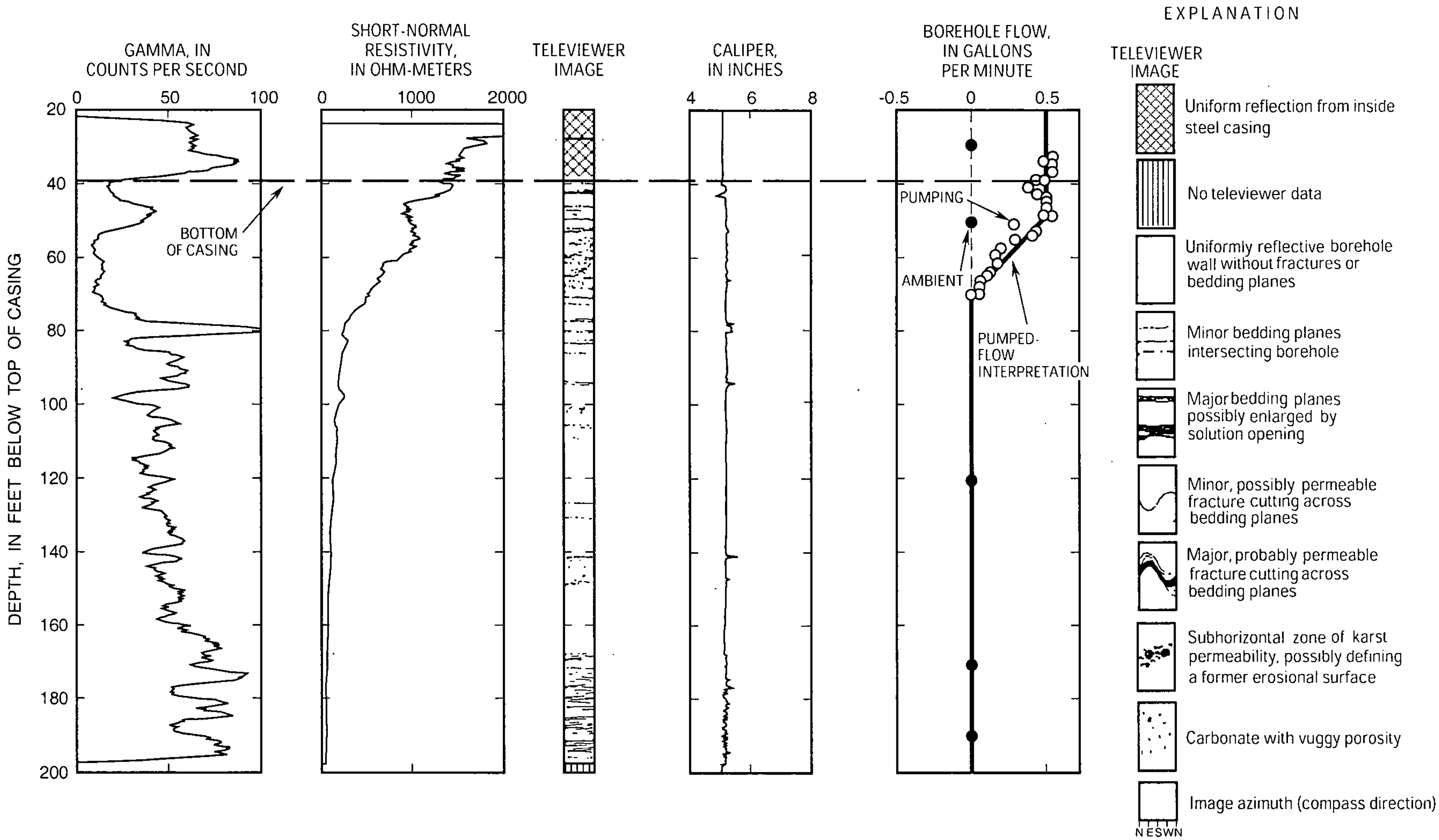


Figure 8. Background geophysical and vertical-flow logs for well JPG-1, June 1999, Jefferson Proving Ground, Indiana.

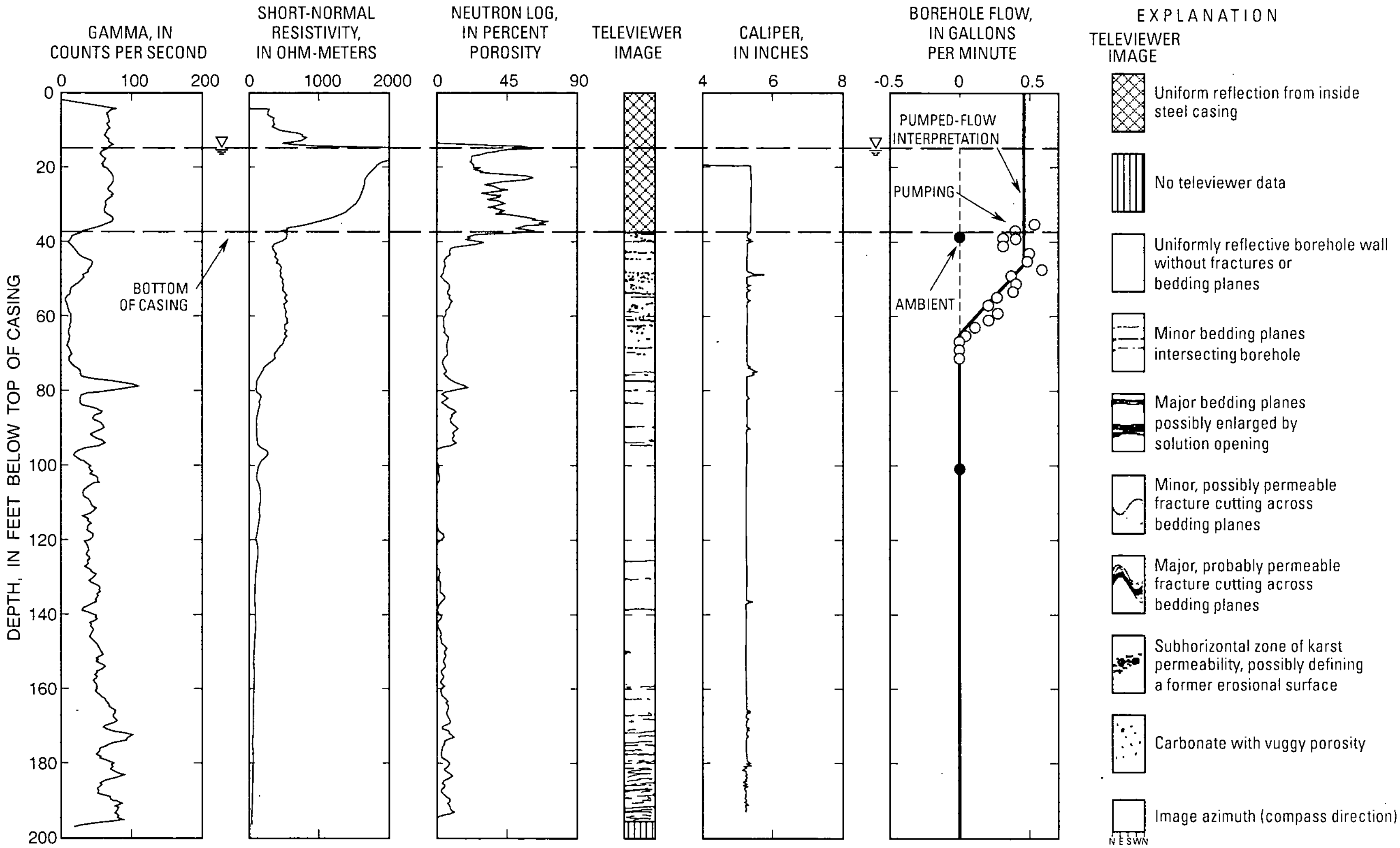


Figure 9. Background geophysical and vertical-flow logs for well JPG-2, June 1999, Jefferson Proving Ground, Indiana.

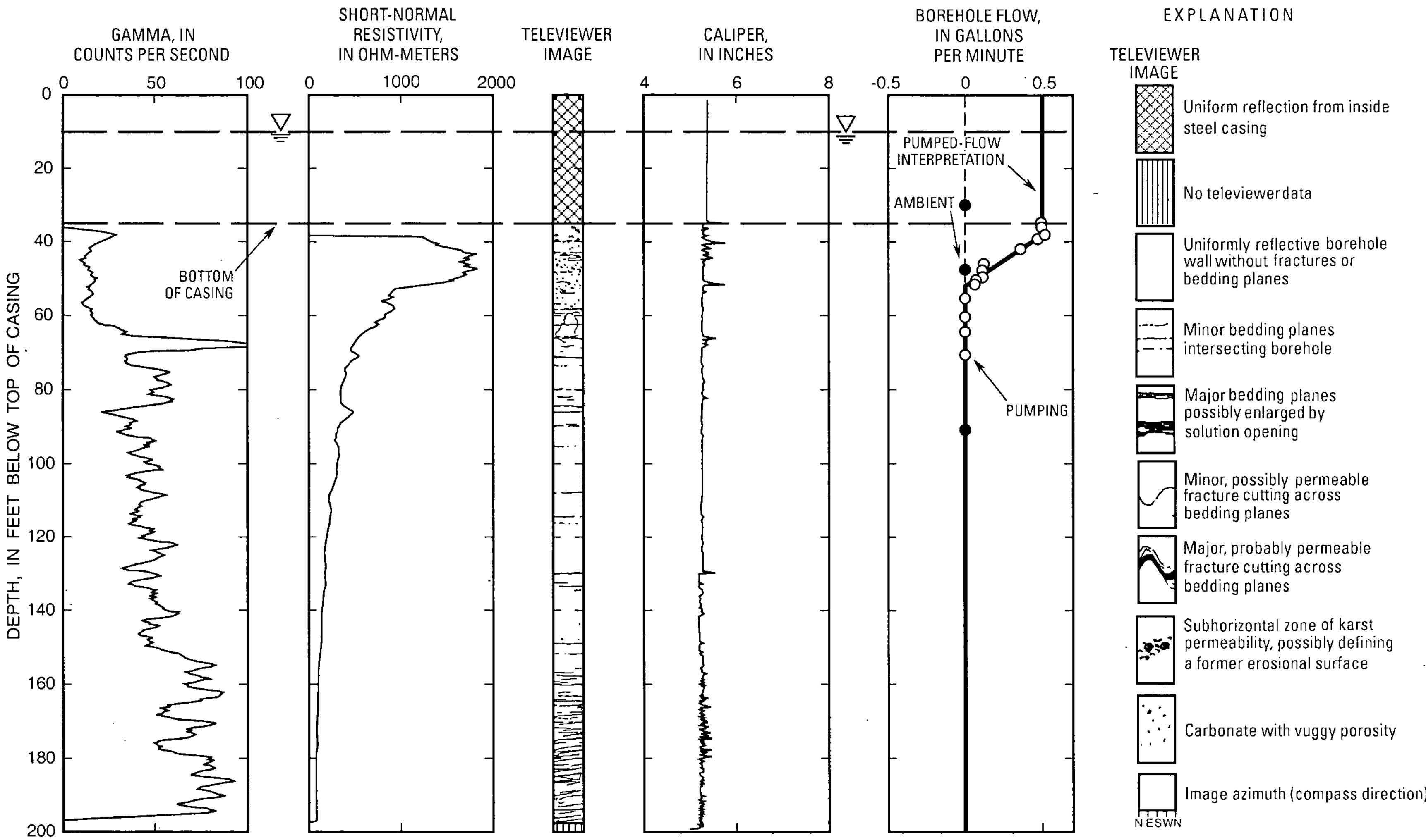


Figure 10. Background geophysical and vertical-flow logs for well JPG-5, June 1999, Jefferson Proving Ground, Indiana.

The neutron log indicates that the primary porosity of the shale-free interval is about 10 percent. The larger neutron-porosity values just below the shale-free interval (for example, from 75 to 95 ft in fig. 9) are attributed to noneffective porosity of clay minerals, indicated by the close correspondence between the gamma and neutron logs. Below about 95 ft, the neutron log indicates massive impermeable rock, with noneffective porosity of clay minerals increasing below 130 ft.

The acoustic-televiewer logs for the JPG test wells indicate a few minor bedding planes over the interval from the bottom of the casing to about 100 ft and abundant bedding planes in the shaly zone below 160 ft. The bedding planes indicated by the televiewer image generally correlate with the caliper logs in figures 8 through 10. The televiewer shows one faint and probably impermeable fracture in test well JPG-5 (60–65 ft in depth) and none in the other two test wells. Vuggy permeability also is indicated in the clay-free interval, as shown by the correlation between low gamma activity and indications of vuggy porosity on the televiewer image.

The vertical-flowmeter logs indicated no vertical flow under ambient conditions in any of the JPG test wells. The flow logs under pumping conditions indicated all inflow was produced from the clay-free zone of low gamma activity or from the minor bedding planes just above that zone. For example, the vertical-flow distribution during pumping (fig. 9) shows all inflow was distributed evenly over the interval from below 48 ft (where all of the 0.5-gal/min flow produced by the pump was measured) to 65 ft (below which depth no upflow could be detected). This distribution of flow indicates that almost all water production in the JPG test wells is associated with the upper half of the vuggy dolomite bed and possibly with the bedding planes just above that bed. Using the flow-profile inversion technique of Paillet (2000), the water-producing zone in the three JPG test wells is assigned a transmissivity value ranging from 7 to 12 ft^2/d (table 1). Hydraulic conductivity is estimated to average from 0.35 to 0.8 ft/d, based on a zone thickness of 15 to 20 ft. The actual vertically averaged horizontal velocity through this zone in the vicinity of the JPG test wells at the time of the horizontal-flowmeter testing would be the product of this average hydraulic conductivity and the local hydraulic head gradient in the aquifer.

The results of the vertical-flow log analyses in the test wells at JPG indicate that the most transmissive interval in each of the test wells is the upper half of the approximately 20-ft-thick bed of porous dolomite just below the bottom of the casing, including the bedding planes just above the top of that bed. The flowmeter profiles indicate that the inflow is distributed evenly over the thickness of this zone. Borehole-flow conditions, however, average the flow response over a vertical distance of at least one borehole diameter. Therefore, thin intervals of concentrated permeability within the zone might not be recognized in the vertical-flow profile. With that qualification, the data indicate that horizontal flow in the JPG test wells most likely is to be found in this transmissive zone. The results also indicate that if test well JPG-1 is pumped, that pumping will induce flow in the porous bed that should be measurable in test well JPG-2. This interpretation is based on the observation that the primary water-producing zone in each of these test wells is within the same stratigraphic interval and is probably laterally continuous over the JPG study area.

Fort Campbell, Kentucky/Tennessee

Three wells—FC-15, FC-16, and FC-29—were logged at the Fort Campbell site (figs. 11–13). Gamma, normal-resistivity, caliper, and televiewer logs were run in each of the wells. As in the JPG test-well logging, a neutron log was run in only one of these wells. The neutron-porosity log in test well FC-29 (fig. 11) gave estimates of primary porosity within laterally continuous strata that were assumed to apply to those strata for each of the test wells. The neutron log showed negligible effective primary porosity for all strata, as indicated by the close correlation between gamma and neutron logs. The only exception is for the major solution openings along bedding planes indicated on the televiewer log for test well FC-29 (fig. 11). Vertical-flow logs were run in each of the test wells under ambient and pumping conditions. Measurable ambient flow was detected in two test wells (FC-29 and FC-15).

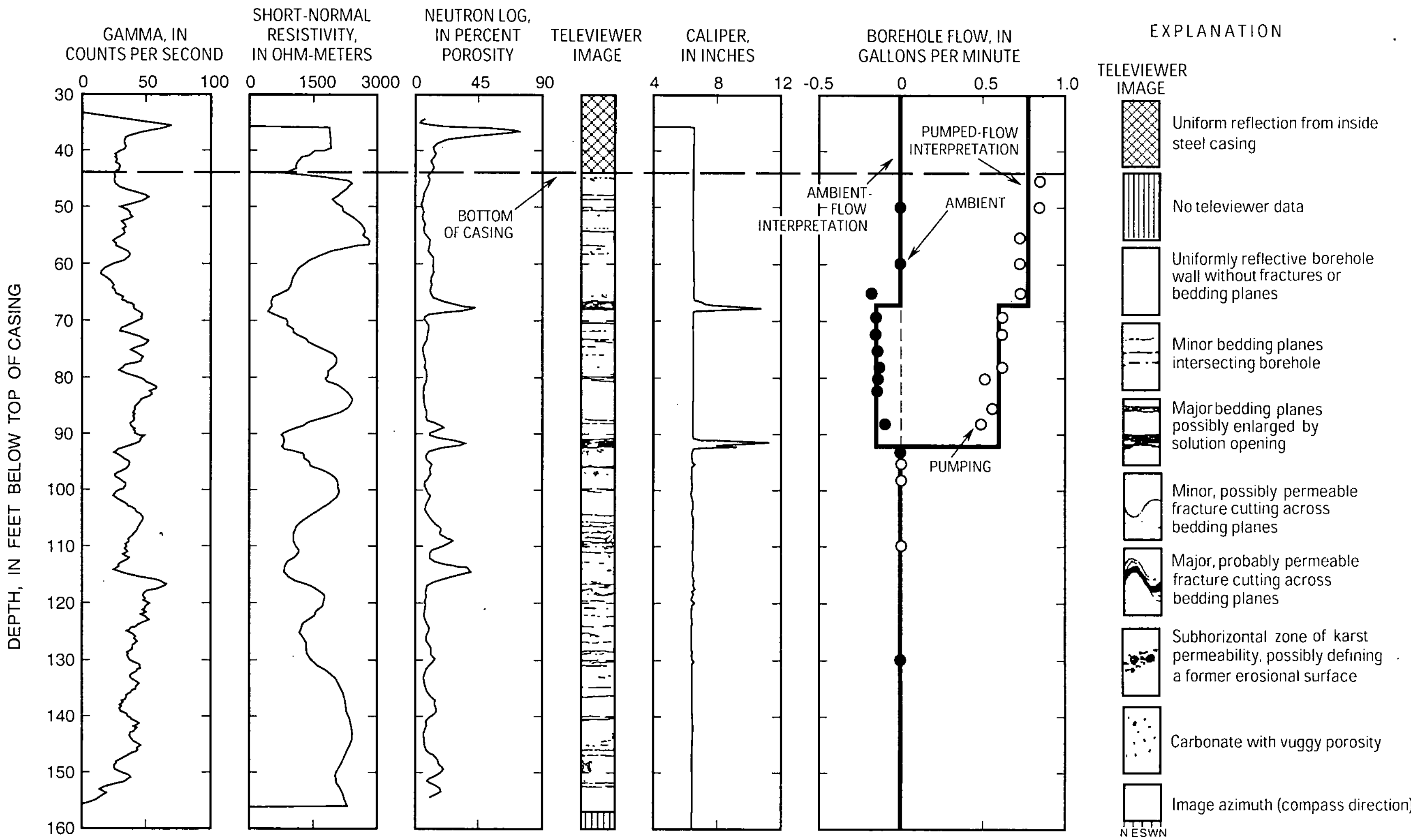


Figure 11. Background geophysical and vertical-flow logs for well FC-29, June 1999, Fort Campbell, Kentucky.

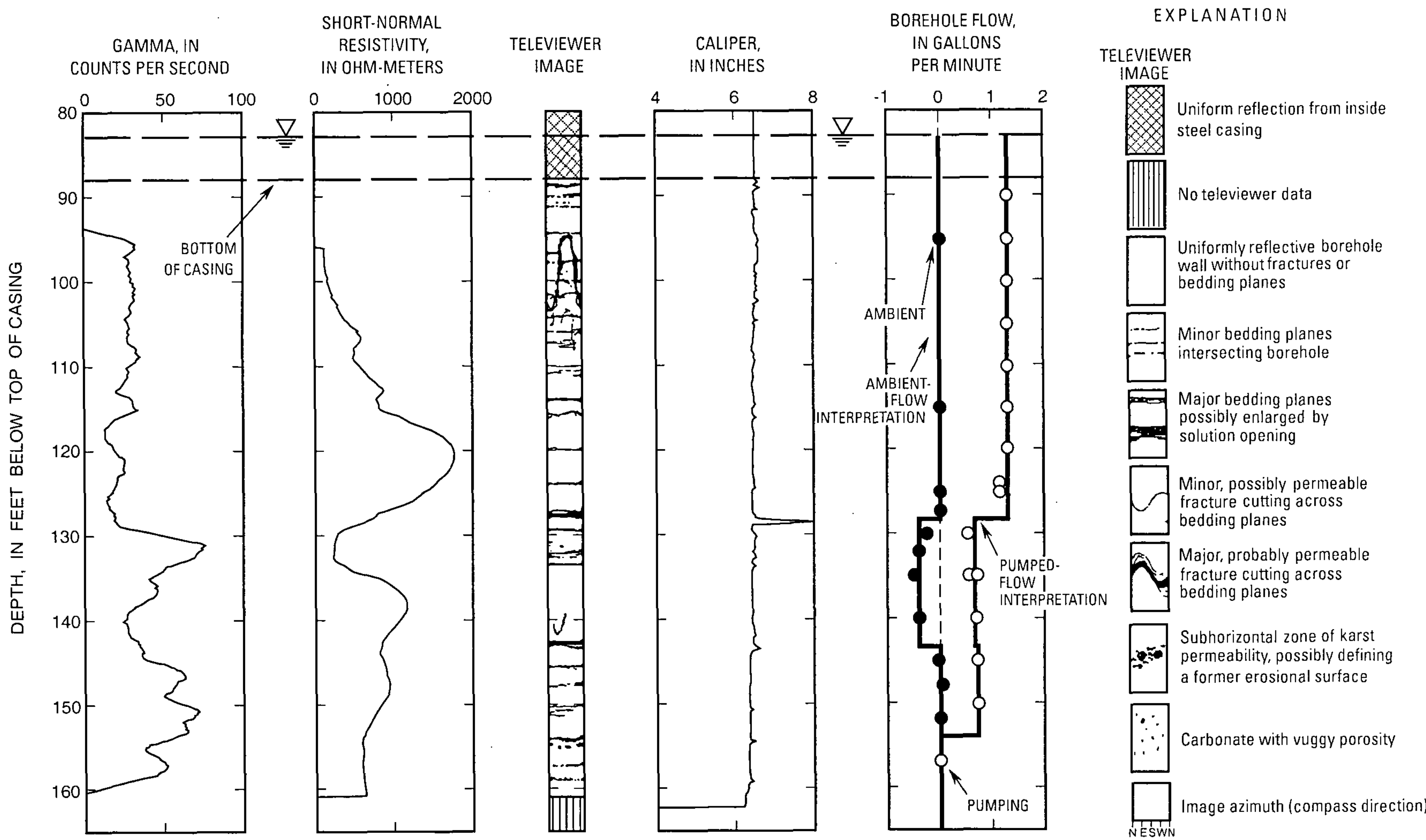


Figure 12. Background geophysical and vertical-flow logs for well FC-15, June 1999, Fort Campbell, Tennessee.

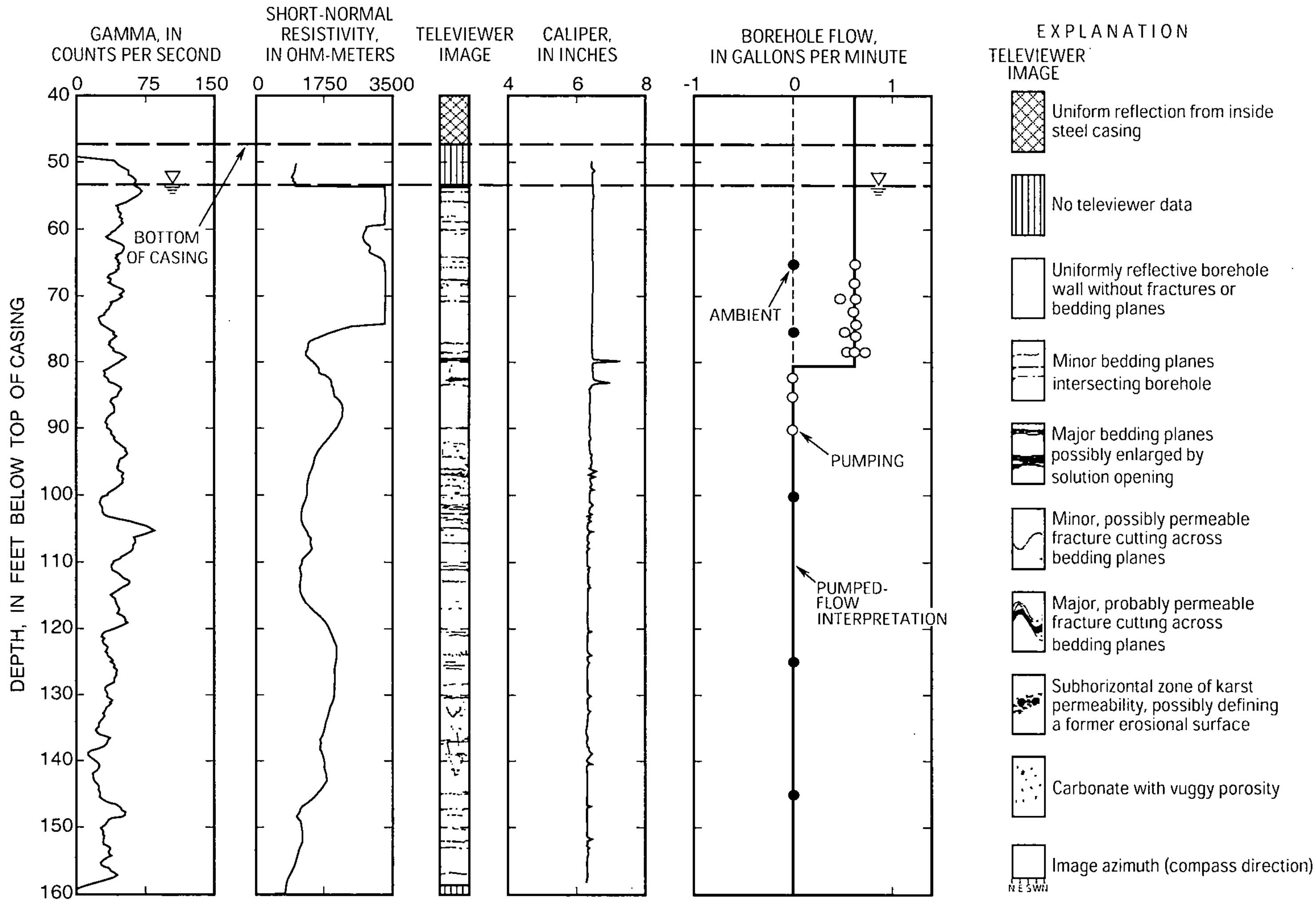


Figure 13. Background geophysical and vertical-flow logs for well FC-16, June 1999, Fort Campbell, Kentucky.

Using the flow-profile inversion technique of Paillet (2000), the water-producing zones in the three test wells at Fort Campbell were assigned transmissivity values ranging from 10 to 700 ft^2/d (table 1). Hydraulic head differences driving the ambient flow were estimated at about 0.5 ft for well FC-29 and 2.5 ft for well FC-15.

On the basis of the geophysical and flowmeter logs in figures 11 through 13, horizontal flow in the vicinity of the three test wells is confined to the bedding-plane fractures associated with inflow or outflow under ambient and pumping conditions. It is difficult or impossible to assign a permeability to each of these bedding-plane zones because a definite thickness cannot be assigned to them. In addition, the irregular solution openings along such bedding planes probably cannot be modeled as thin layers of homogeneous porous medium. The caliper log can be used to define an upper limit for the thickness of the bedding planes, as indicated in table 1. Using those estimated thicknesses and the approximation of each bedding-plane zone in figures 11 through 13 as a thin porous bed, the estimates of hydraulic conductivity range from 10 to 350 ft/d.

The presence of thin zones of relatively high permeability between long intervals of effectively impermeable bedrock poses several problems for the testing of horizontal flowmeters at the Fort Campbell site. The small interval of intersection with the borehole indicates that great care be used in stationing each horizontal flowmeter for the flow tests to ensure that the measurement is made precisely where the permeable bedding plane intersects the borehole. The lack of homogeneity in the distribution of permeability within each bedding plane further complicates the task of ensuring that flow measurements made with different equipment are made at precisely the same position.

The presence of strong vertical flow along the borehole between permeable bedding planes also complicates horizontal-flow measurements. Although there might be horizontal flow across the borehole under ambient conditions, that flow would be superimposed on a larger vertical flow. This vertical-flow regime would include horizontal flow entering the borehole at one bedding plane and exiting at another, even though the direction of this flow is vertical in the interval between bedding planes where there is no horizontal flow. Horizontal flowmeters making point measurements of flow within the open borehole (acoustic Doppler velocimeter and colloidal borescope) may not be able to distinguish the borehole inflow or outflow (needed to balance the ambient vertical-flow regime) from the small amount of continuous horizontal flow in each of the bedding-plane zones for wells FC-29 and FC-15. Even when baffles or flexible disks are used to prevent vertical flow in the borehole at the flow-measurement station, the seal never can be fully effective, and appreciable vertical flow probably would be superimposed on the horizontal-flow field. When vertical flow exists in the borehole, the use of packer devices probably is required to make definitive measurements of the natural horizontal flow.

Selection of Measuring Zones

The depths for measuring horizontal flow were selected through an evaluation process that included a combination of the background geophysical logs (specifically the acoustic-televiewer and caliper logs) the vertical-flow logging, and visual observations with a borehole camera. The acoustic-televiewer and caliper logs were used to identify potential bedding planes and fractures intercepted by the borehole. The vertical-flow logging identified which of these features produced water within the resolution of the vertical heat-pulse flowmeter. A borehole camera was provided with the first horizontal flowmeter tested. The borehole camera was used to make visual observations of the features shown in the acoustic-televiewer and caliper logs and to verify the depths of the features. The borehole camera was deployed on aluminum rods of known length, providing accurate depth measurements. The borehole camera also was used to identify the bottom of the casing and to determine the width of the open fractures at Fort Campbell.

It is important to note that not all of the measuring points needed to have flow for this study. The ability to correctly measure zero flow where there is no flow would be a valuable characteristic of the flowmeters. The results of the vertical-flowmeter logging indicated that the wells at JPG did not have any distinct zones with high transmissivity. In an attempt to provide a wider range of measurable horizontal-flow velocities, a cross-hole test was included where well JPG-1 was pumped while measurements were made in well JPG-2. Well JPG-1 is approximately 150 ft northwest from well JPG-2, along an azimuth (compass direction) of 300 degrees from JPG-2.

The preselection of measurement zones was necessary to ensure that the contractors made measurements at the same locations in each of the wells. Time was an issue because measurements had to be made at numerous depths in six wells. As time permitted, the contractors could make additional measurements at different depths or repeat measurements at the same depth. Having preselected measurement depths was not necessarily compatible with the standard methods of the contractors. Through development of their instruments, the contractors have established methods for evaluating wells and finding preferential flow zones in wells; it is possible that the contractors may have found more flow zones or better flow zones than those preselected for measurements in this study. For more detail on the contractors' methods, refer to the Kearl, Kerfoot, and Pedler references cited at the end of this report.

Horizontal Heat-Pulse Flowmeter

The KVA flowmeter was the first of the flowmeters to be tested. Measurements were made August 23–28, 1999, with one well completed each day. Measurements were made at JPG, August 23–25. Flow in well JPG-5 was measured under ambient conditions, and flow in well JPG-2 was measured under ambient conditions and while pumping nearby well JPG-1. Measurements were made at Fort Campbell, August 26–28. Wells FC-29, FC-15, and FC-16 were tested under ambient conditions. Generally, all of the flowmeter equipment was tested under summer drought conditions in which the ground-water levels gradually were falling. Ground-water levels measured during the study are shown in figure 6 for JPG and figure 7 for Fort Campbell. These water levels are considered representative of the hydrologic conditions at each site for the period of study covering all of the flowmeter tests.

The results of the KVA flowmeter measurements are listed in tables 2 to 8; the depths of the measuring points are referenced to the top of the well casing. Each measurement typically required 30 to 45 minutes, which included carefully moving the probe to the next measurement depth and waiting for the water column to equilibrate. Moving the probe in the low-permeability formation of the JPG wells caused a noticeable displacement of the water level. Moving the probe in the open part of the boreholes required more caution than that required in the casing. The fuzzy packer had a tendency to catch on the irregular texture of the borehole wall and met enough resistance in wells JPG-5, JPG-2, and FC-29 that some of the deeper zones of interest could not be reached because of potential damage to the fuzzy packer. The wells at JPG required a fuzzy packer with a diameter of slightly more than 5 inches, and the wells at Fort Campbell required a fuzzy packer with a diameter of slightly more than 6.25 inches. Not all features identified on the caliper and acoustic-televiewer logs could be evaluated with the KVA flowmeter. The number of measurements at each well was limited to how much could be done in a workday.

In well JPG-5 the bottom of casing was 34.6 ft below the top of casing. The static water level at the time of the KVA measurements was 11.5 ft below the top of casing. Ten measurements were made, of which one was a repeat, from depths of 39.00 to 51.30 ft. The measurements were concentrated in the zone that the vertical-flow analysis determined was water producing (table 1, fig. 10). The background geophysical logging determined that this zone was consistent in the three wells at JPG. This massive, clean dolomite layer had some subtle bedding planes visible in the acoustic-televiewer logs and the borehole camera display, but the layer was more characteristic of vuggy porosity. There were no visibly open bedding planes or fractures in the wells at JPG. For calibrating the flow velocities in well JPG-5, the estimated transmissivity for this zone was used to estimate the hydraulic conductivity (0.8 ft/d).

The measurements in well JPG-5 form two distinct groups based on the direction of flow; the upper four measurements indicate a flow direction to the south-southeast, averaging 159 degrees (table 2). The five lower measurements indicate a flow direction to the northeast, averaging 60 degrees. There was no apparent difference in the velocities measured in these two zones; the measured velocities in the borehole covered a small range of 0.65 to 3.6 ft/d. The trend of the regional water table, based on the limited number of available wells, is to the southwest (fig. 6), which is the direction of bedrock dip. The measurement repeated at a depth of 40.10 ft produced a direction of almost 90 degrees from the original measurement (154 degrees to 66 degrees) and a velocity more than twice that of the original (1.65 to 3.6 ft/d) (fig. 14).

The corrected velocities or seepage velocities in the aquifer, V_o, for the measurements at JPG were determined from a ratio of equation 1 for the calibration chamber and the field conditions. The hydraulic conductivity of the formation, K_o, was estimated to be 0.8 ft/d in well JPG-5. Solving equation 2 for the calibration chamber yields

$$K_r cal = \frac{670}{200} = 3.35$$

Solving equation 2 for the field conditions yields

$$K_r\ field = \frac{670}{0.8} = 837.5$$

The flow-magnification factor for the calibration chamber was determined, using equation 1

$$f_{cal} = \frac{2(3.35)}{1 + 3.35} = 1.54$$

Table 2. Borehole measurements of ground-water flow made with the KVA flowmeter in well JPG-5, Jefferson Proving Ground, Indiana, August 23, 1999

[Depth is measured from top of casing; ft, foot; Flow direction is compass direction relative to magnetic north; ft/d, foot per day; V_0, estimated seepage velocity of the aquifer; NR, no remark]

Depth (ft)	Time	Flow direction (degrees)	Velocity (machine units)	Velocity in borehole (ft/d)	Corrected velocity, V_0 (ft/d)	Remarks
39.00	12:00	136	52	1.85	1.4	NR
39.50	12:50	180	37	1.31	1.0	NR
40.10	13:30	154	46	1.65	1.3	NR
41.60	14:15	167	26	.95	.7	NR
43.00	14:45	76	71	2.55	2.0	NR
44.10	15:15	52	21	.75	.6	NR
45.00	15:45	26	33	1.20	.9	NR
40.10	16:30	66	101	3.60	2.8	Repeat
50.70	17:00	78	18	.65	.5	NR
51.30	17:45	69	40	1.45	1.1	NR

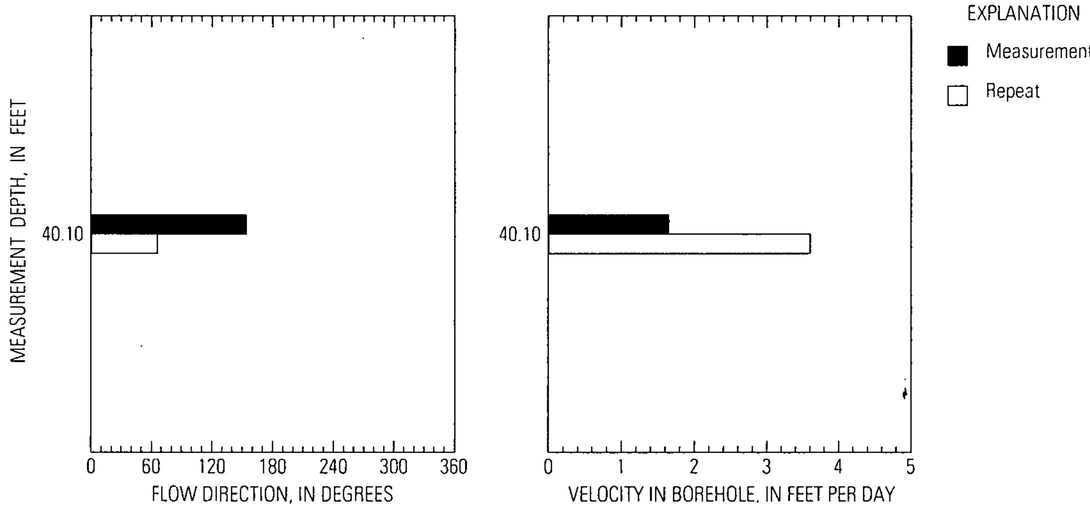


Figure 14. Flow directions and velocities for two measurements made with the KVA flowmeter at a depth of 40.10 feet in well JPG-5, Jefferson Proving Ground, Indiana.

Solving for the flow-magnification factor for the field conditions at well JPG-5 yields

$$f_{field} = \frac{2(837.5)}{1 + 837.5} = 2.00$$

The ratio of f_{cal} to f_{field} equals 0.77,

which is the multiplication factor applied to the velocities measured in the borehole to give the seepage velocities in the aquifer. The resulting magnification factor of the borehole would be $1/0.77$, or 1.3 times the seepage velocity in the aquifer.

The velocity measurements made in well JPG-2 under ambient conditions are listed in table 3. The static water level was 16.1 ft below the top of casing. Thirteen measurements were made at depths of 41.75 to 60.76 ft. One repeat measurement was made at a depth of 50.34 ft, the depth that yielded the highest measured velocity in the well for the first measurement. The upper two measurements in well JPG-2 were indeterminate for velocity and direction, which is reasonable, given that they were made above the water-producing zone determined from the vertical-flow analysis.

The measurements consistently showed a flow direction to the northwest, ranging from 270 to 353 degrees and averaging 309 degrees. The velocities measured in the borehole covered a small range of 0.8 to 4.4 ft/d. The measurement repeated at a depth of 50.34 ft had a flow direction 33 degrees from the first measurement (275 degrees to 308 degrees) and a velocity less than one half the first (4.4 to 1.7 ft/d) (fig. 15).

The velocity measurements made in well JPG-2 while pumping nearby well JPG-1 are listed in table 4. Twelve measurements were made over the same depth range as during the ambient measurements. The first measurement was made at a depth of 50.34 ft prior to pumping (table 4). This depth was measured twice the previous day under ambient conditions (table 3). The directions of flow for the three measurements at 50.34 ft were 275, 308, and 353 degrees, and the velocities in the borehole were 4.4, 1.7, and 2.17 ft/d (fig. 15).

After the ambient measurement was made at 50.34 ft, the pump was turned on (at 09:21) in well JPG-1. The remainder of the measurements in table 4 were made while well JPG-1 was being

Table 3. Borehole measurements of ground-water flow made with the KVA flowmeter in well JPG-2, Jefferson Proving Ground, Indiana, August 24, 1999

[Depth is measured from top of casing; ft, foot; Flow direction is compass direction relative to magnetic north; ft/d, foot per day; V_0, estimated seepage velocity of the aquifer; --, velocity and direction were indeterminate, implying little or no flow; NR, no remark]

Depth (ft)	Time	Flow direction (degrees)	Velocity (machine units)	Velocity in borehole (ft/d)	Corrected velocity, V_0 (ft/d)	Remarks
41.75	11:00	--	--	--	--	NR
42.17	11:30	--	--	--	--	NR
44.01	12:10	351	57	2.05	1.6	NR
46.53	12:45	307	42	1.50	1.2	NR
48.66	13:20	311	38	1.35	1.1	NR
50.34	13:50	275	123	4.40	3.4	NR
53.48	14:45	294	23	.80	.6	NR
54.02	15:10	290	44	1.50	1.2	NR
55.51	15:45	331	40	1.30	1.0	NR
57.38	16:25	270	69	2.45	1.9	NR
58.38	17:00	353	35	1.25	1.0	NR
60.76	17:35	305	33	1.20	.9	NR
50.34	18:35	308	47	1.70	1.3	Repeat

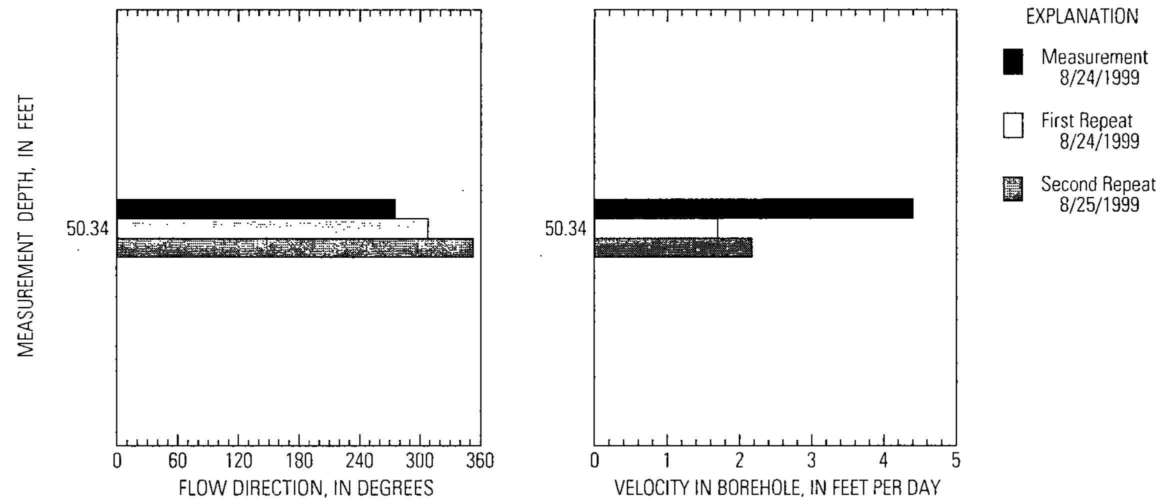


Figure 15. Flow directions and velocities for multiple measurements made with the KVA flowmeter at a depth of 50.34 feet in well JPG-2, Jefferson Proving Ground, Indiana.

Table 4. Borehole measurements of ground-water flow made with the KVA flowmeter in well JPG-2 while pumping nearby well JPG-1, Jefferson Proving Ground, Indiana, August 25, 1999

[Depth is measured from top of casing; ft, foot; Flow direction is compass direction relative to magnetic north; ft/d, foot per day; V_0, estimated seepage velocity of the aquifer; NR, no remark]

Depth (ft)	Time	Flow direction (degrees)	Velocity (machine units)	Velocity in borehole (ft/d)	Corrected velocity, V_0 (ft/d)	Remarks
50.34	09:00	353	61	2.17	1.7	Pump off
50.34	09:55	126	655	23.4	18.0	NR
50.34	10:20	107	322	13.4	10.3	Repeat
48.66	10:50	110	84	3.00	2.3	NR
48.66	11:10	146	85	3.00	2.3	Repeat
46.53	11:30	158	56	2.00	1.5	NR
44.01	11:55	218	148	5.30	4.1	NR
53.48	13:15	253	10	.40	.3	NR
54.02	13:35	337	40	1.40	1.1	NR
57.38	14:20	44	81	2.90	2.2	NR
58.38	14:45	103	22	.80	.6	NR
50.34	15:20	112	96	3.40	2.6	Repeat

pumped at an average rate of 0.71 gal/min. Two measurements were made at a depth of 50.34 ft during the early part of the pumping. These measurements resulted in similar flow directions (126 degrees and 107 degrees), but the first velocity was almost twice the second (23.4 and 13.4 ft/d) (table 4, fig. 16). A third measurement was made at this depth near the end of the pumping, almost 5 hours after the first measurement. The flow direction of the third measurement was consistent with the first two (112 degrees), but the velocity in the borehole (3.4 ft/d) was lower than the previous two and more similar to the ambient measurements. This decline in the velocity with time, for the same depth, may indicate that the earlier measurements are affected by drawdown in well JPG-2. Drawdown curves for the two wells are shown in figure 17. Well JPG-2 was instrumented with a pressure-sensor transducer to continuously record the water level.

Two measurements also were made at a depth of 48.66 ft. The repeat measurement had a flow direction 36 degrees from the first measurement (110 degrees to 146 degrees) and a velocity that matched the first measurement of 3.0 ft/d (table 4, fig. 16).

The flow directions measured during pumping were more variable than those measured during ambient conditions. Under ambient conditions, the flow directions generally were to the northwest; under pumping conditions, the flow directions generally were to the southeast—in the opposite direction of the pumped well. Only one measurement under pumping conditions showed a flow direction to the northwest—the measurement at 54.02 ft had a flow direction of 337 degrees.

The depths at which measurements were made under the ambient and pumping conditions are listed in table 5. Well JPG-1 is about 150 ft northwest from JPG-2 at an azimuth of 300 degrees; therefore, it would be expected that the flow direction under pumping conditions would be towards well JPG-1. The drawdown curves show that a water-level difference of about 11 ft developed between the two wells during the pumping (fig. 17). The measured velocities in the borehole were

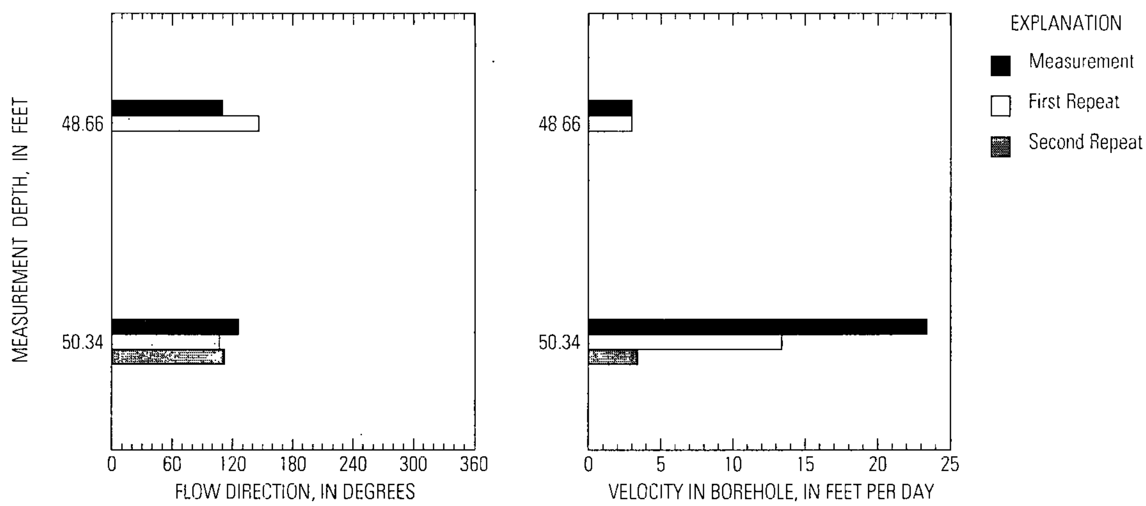


Figure 16. Flow directions and velocities for multiple measurements made with the KVA flowmeter at selected depths in well JPG-2, while pumping nearby well JPG-1, Jefferson Proving Ground, Indiana.

Table 5. Borehole measurements of ground-water flow made with the KVA flowmeter in well JPG-2 for ambient conditions and while pumping nearby well JPG-1, Jefferson Proving Ground, Indiana, August 24–25, 1999

[Depth is measured from top of casing; ft, foot; Flow direction is compass direction relative to magnetic north; ft/d, foot per day; NM, no measurement]

Depth (ft)	Flow direction while ambient (degrees)	Flow direction while pumping (degrees)	Velocity in borehole while ambient (ft/d)	Velocity in borehole while pumping (ft/d)	Elapsed pumping time (minutes)
44.01	351	218	2.05	5.30	154
46.53	307	158	1.50	2.00	129
48.66	311	110	1.35	3.00	89
48.66	NM	146	NM	3.00	109
50.34	275	126	4.40	23.4	34
50.34	308	107	1.70	13.4	59
50.34	353	112	2.17	3.40	359
53.48	294	253	.80	.40	234
54.02	290	337	1.50	1.40	254
57.38	270	44	2.45	2.90	299
58.38	353	103	1.25	.80	324
Average	**311**	**156**	**1.9**	**5.4**	not averaged

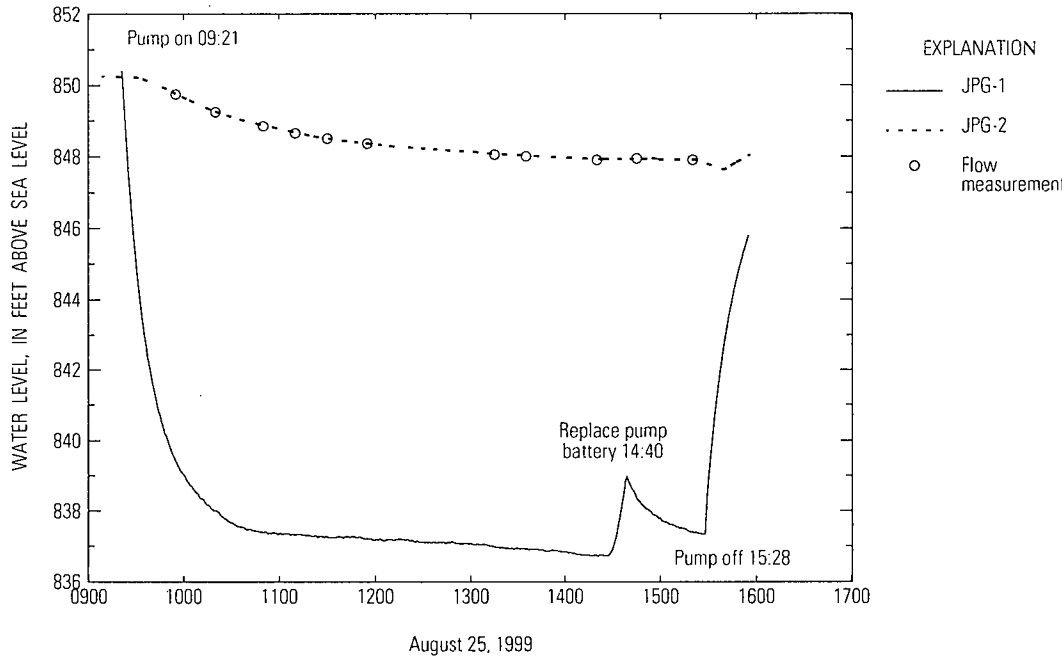


Figure 17. Drawdown curves for well JPG-2 and nearby well JPG-1, which was pumped at 0.71 gallon per minute, while measurements were made with the KVA flowmeter in well JPG-2, Jefferson Proving Ground, Indiana.

higher under pumping conditions than under ambient conditions, with the exception of three instances. Two of the measurements made at a depth of 50.34 ft had velocities much higher than velocities measured at this depth under ambient conditions (table 5). Because of the time variable, differences in the directions and velocities in table 5 were not computed; however, the data are presented to show the relative differences and the general trends.

Although the velocities measured with the KVA flowmeter were somewhat higher during the pumping, the measurements did not show the anticipated effect of flow directions towards the pumping well. The pumping time was probably insufficient to cause a consistent increase in velocity and to cause a complete change in flow direction towards the pumping well. The response in the low-permeability bedrock was more delayed than in a highly permeable sand aquifer or in bedrock with open fractures. Even though well JPG-2 was in hydraulic connection with well JPG-1, it is possible that some of the tested zones were not.

The corrected velocity or seepage velocity in the aquifer, V_o, for well JPG-2 was determined, using the same method as described for well JPG-5 (p. 36). The hydraulic conductivity of the formation, K_o, was estimated to be 0.45 ft/d at well JPG-2. Therefore,

K_r *field* was determined to be 1,488

and f_{field} was determined to be 2.0.

The ratio of f_{cal} to f_{field} equals 0.77,

which is the multiplication factor applied to the velocities measured in the borehole to give the seepage velocities in the aquifer. The resulting magnification factor of the borehole would be $1/0.77$, or 1.3 times the seepage velocity in the aquifer.

The results of the KVA flowmeter measurements at Fort Campbell are listed in tables 6 to 8. The background geophysical logging indi-

Table 6. Borehole measurements of ground-water flow made with the KVA flowmeter in well FC-29, Fort Campbell, Kentucky, August 26, 1999

[Depth is measured from top of casing; ft, foot; Flow direction is compass direction relative to magnetic north; ft/d, foot per day; V_0, estimated seepage velocity of the aquifer; NR, no remark; --, velocity and direction were indeterminate, implying little or no flow]

Depth (ft)	Time	Flow direction (degrees)	Velocity (machine units)	Velocity in borehole (ft/d)	Corrected velocity, V_0 (ft/d)	Remarks
50.37	11:20	57	8	0.60	0.5	NR
53.92	11:50	276	25	1.80	1.4	NR
65.96	12:30	51	9	.60	.5	.2 ft above fracture
67.20	13:30	30	17	1.20	1.4	Middle of fracture
68.27	13:00	--	--	--	--	.2 ft below fracture
70.00	14:00	--	--	--	--	NR
79.75	14:45	80	20	1.40	1.1	NR
91.42	15:10	305	17	1.20	1.0	Middle of fracture
95.20	15:35	22	14	1.00	.8	NR
102.70	16:00	15	11	.80	.6	NR
68.27	17:00	--	--	--	--	Repeat
65.96	17:30	15	14	1.00	.8	Repeat
53.92	18:00	31	18	1.30	1.0	Repeat

Table 7. Borehole measurements of ground-water flow made with the KVA flowmeter in well FC-15, Fort Campbell, Tennessee, August 27, 1999

[Depth is measured from top of casing; ft, foot; Flow direction is compass direction relative to magnetic north; ft/d, foot per day; V_0, estimated seepage velocity of the aquifer; NR, no remark; --, velocity and direction were indeterminate, implying little or no flow; NM, no measurement]

Depth (ft)	Time	Flow direction (degrees)	Velocity (machine units)	Velocity in borehole (ft/d)	Corrected velocity, V_0 (ft/d)	Remarks
96.80	09:45	209	49	1.75	1.3	NR
104.90	10:25	352	41	1.45	1.1	NR
114.63	11:00	246	33	1.20	.9	NR
116.27	11:30	246	31	1.10	.8	NR
124.41	12:00	231	90	3.20	2.5	NR
128.00	12:30	268	75	2.65	2.0	.2 ft above fracture
128.45	13:10	157	58	2.05	1.7	Middle of fracture
128.90	13:40	--	--	--	--	.2 below fracture
130.10	14:10	266	71	2.55	2.0	NR
143.52	14:40	267	4	.15	.1	Middle of fracture
150.77	15:20	--	--	--	--	NR
154.25	15:45	--	--	--	--	.3 ft above fracture
154.78	NM	NM	NM	NM	NM	Middle of fracture
155.30	16:15	264	54	1.95	1.5	.3 ft below fracture

Table 8. Borehole measurements of ground-water flow made with the KVA flowmeter in well FC-16, Fort Campbell, Kentucky, August 28, 1999

[Depth is measured from top of casing; ft, foot; Flow direction is compass direction relative to magnetic north; ft/d, foot per day; V_0, estimated seepage velocity of the aquifer; --, velocity and direction were indeterminate, implying little or no flow; NR, no remark]

Depth (ft)	Time	Flow direction (degrees)	Velocity (machine units)	Velocity in borehole (ft/d)	Corrected velocity, V_0 (ft/d)	Remarks
78.50	07:35	--	--	--	--	NR
80.46	08:10	295	443	15.8	12.2	.3 ft above fracture
80.91	08:40	212	16	.55	.4	Middle of fracture
81.36	09:05	123	14	.50	.4	.3 ft below fracture
84.90	09:30	278	33	1.20	.9	NR
97.30	09:55	103	9	.30	.2	NR
104.83	10:30	96	14	.50	.4	NR
130.90	11:05	139	22	.80	.6	NR
147.65	11:40	108	20	.70	.5	NR

cated that well FC-29 had two open fractures or dissolution-enhanced bedding planes that produced water (table 1, fig. 11). These two features are noticeable on the caliper and acoustic-televiewer logs at depths of 67.20 ft and 91.42 ft. The caliper and acoustic-televiewer logs indicated that both features were about 2 ft wide. Visual observation with the borehole camera indicated the upper fracture was about 1.9 ft wide and the lower fracture was about 1.3 ft wide. The vertical-flow logging during June 1999 indicated water flowed (about 0.15 gal/min) from the upper fracture down the borehole to the lower fracture (fig. 11). The static water level at the time of the KVA measurements was 39.12 ft below the top of casing.

Thirteen measurements were made in well FC-29, of which three were repeat measurements (table 6). Measurements were made at the middle of both fractures but, because the fractures were wider than the height of the fuzzy packer, the data possibly are inaccurate. If the fuzzy packer does not maintain contact with the borehole wall, flow will bypass the flowmeter rather than pass through the fuzzy packer and glass beads. The ambient vertical flow in FC-29 also presented a problem for measuring horizontal flow. If the fuzzy packer does not fit snugly against the borehole wall, the vertical flow will not be sealed off. Because of vertical flow between the two fractures, the measurements between the depths of 65.96 and 91.42 ft should be considered suspect. Measurements were not made below a depth of 102.70 ft because the fuzzy packer was caught on the borehole wall just below that depth.

Most of the measurements in FC-29 indicate a north to northeast flow direction. If the measurement at the middle of the deeper fracture (91.42 ft) is discounted, only one measurement indicated a westerly flow (53.92 ft). All velocities measured in the borehole were similar—roughly 1 ft/d. The last three measurements in table 6 are repeat measurements at depths of 53.92, 65.96, and 68.27 ft. The two measurements at 53.92 ft produced similar velocities in the borehole (1.8 and 1.3 ft/d), but the flow directions differed by 115 degrees (276 degrees and 31 degrees) (fig. 18). The two measurements at 65.96 produced similar velocities in the borehole (0.6 and 1.0 ft/d), but the flow directions differed by 36 degrees (51 degrees and 15 degrees). Both measurements at 68.27 ft were indeterminate, equating to zero or near-zero velocity.

The corrected velocity or seepage velocity in the aquifer, V_0, required multiple corrections because of the two open fractures in well FC-29

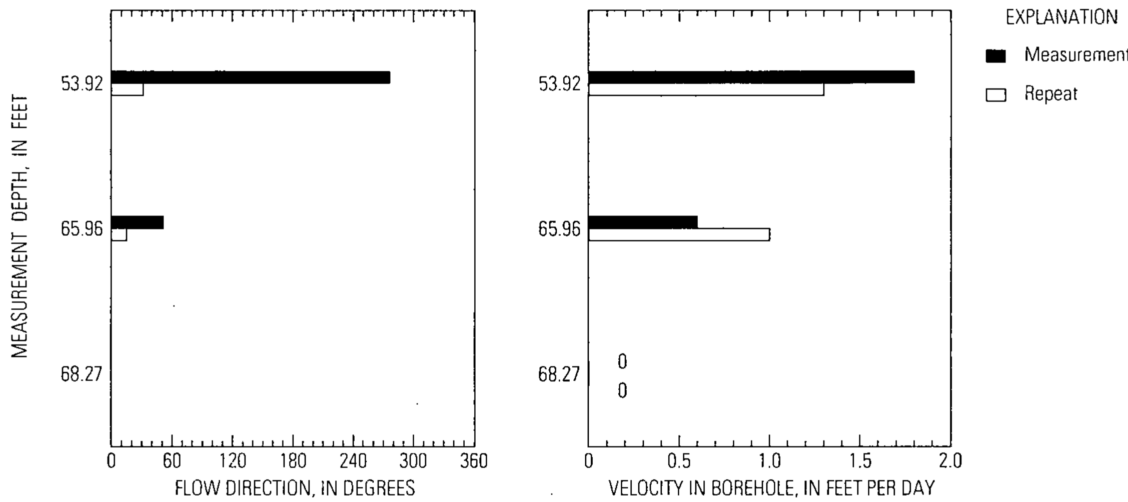


Figure 18. Flow directions and velocities for two measurements made with the KVA flowmeter at selected depths in well FC-29, Fort Campbell, Kentucky.

and the low-conductivity formation elsewhere. The upper fracture in well FC-29 was estimated to have a hydraulic conductivity of 350 ft/d, and the lower fracture was estimated to have a hydraulic conductivity of 35 ft/d (based on estimates of zone transmissivity and thickness for the background geophysical logging listed in table 1). The vertical-flow logging did not identify other water-producing zones in well FC-29; therefore, the remainder of the well was assumed to have a very low hydraulic conductivity. Under these conditions, the value of

f_{field} would equal the maximum of 2.0 and the ratio of f_{cal} to f_{field} would equal 0.77.

Because of the high conductivity of the upper fracture, the measurement at 67.20 ft had a ratio of

f_{cal} to f_{field} equal to 1.17.

The ratio of f_{cal} to f_{field} for the measurement at the lower fracture at 91.42 ft equals 0.81. Because the fractures in well FC-29 are wider than the height of the fuzzy packer, however, the measured velocities are suspect because of flow potentially bypassing the fuzzy packer, resulting in an artificially low velocity.

The background geophysical logging indicated that well FC-15 had three open fractures or dissolution-enhanced bedding planes that produced water (table 1, fig. 12). These three features are noticeable on the caliper and acoustic-televiewer logs, which indicated that the upper two fractures were about 1 ft wide and the lower fracture was about 0.5 ft wide. Visual observation with the borehole camera indicated that the first (upper) fracture was about 0.5 ft wide at a depth of 128.45 ft, the second (middle) fracture was about 0.3 ft wide at a depth of 143.52 ft, and the third (lower) fracture was about 0.5 ft wide at a depth of 154.78 ft. The vertical-flow logging from June 1999 indicated that under ambient conditions, there was strong flow (about 0.4 gal/min) from the upper fracture down to the middle fracture and a slight flow (about 0.08 gal/min) from the lower fracture up to the middle fracture (fig. 12).

Thirteen measurements were made in well FC-15, three of which were indeterminate (table 7). Measurements were made at the middle of the first and second fractures, but these measurements would be subject to the same constraints previously discussed for well FC-29. Most of the measurements in FC-15 indicate a flow direction of west to southwest, but two measurements did not fit this trend. The measurement at 104.90 ft had a flow direction of 352 degrees, and the measurement at 128.45 (at the middle of the upper fracture) had a flow direction of 157 degrees. The remaining eight measurements, for which a flow direction was determined, had an average flow direction of 250 degrees. The measurements in well FC-15 produced a small range of velocities in the borehole, generally between 1 and 3 ft/d. The measurement at 143.52 ft, which was made at the middle of the second fracture, produced a very low velocity (0.15 ft/d) relative to the other measurements. Such a low velocity may indicate that not all of the flow was passing through the flowmeter.

The fractures in well FC-15 were estimated to have hydraulic conductivities of 42, 42, and 170 ft/d, in descending order (table 1). As for well FC-29, the formation in well FC-15 was assumed to have a very low hydraulic conductivity other than at the open fractures; therefore,

f_{field} would equal the maximum of 2.0,

and the ratio of f_{cal} to f_{field} would equal 0.77.

The measurements at the two fractures (128.45 and 143.52 ft) had a ratio of

f_{cal} to f_{field} equal to 0.82.

The background geophysical logging indicated one open fracture or dissolution-enhanced bedding plane that produced water in well FC-16 (table 1, fig. 13). This opening is noticeable on the caliper and acoustic-televiewer logs at a depth of about 81 ft. Visual observation with the borehole camera indicated that the open fracture was about 0.3 ft wide. The vertical-flow logging indicated no vertical flow in well FC-16 under ambient conditions. The static water level at the time of the KVA measurements was 54.5 ft below the top of casing.

Nine measurements were made in well FC-16, one of which was indeterminate (table 8). The measurements produced a wide range of flow directions and mostly low velocities in the borehole. The two measurements with the highest velocity in the borehole had westerly flow directions (295 degrees and 278 degrees). The measurement at a depth of 80.46 ft produced a borehole velocity of 15.8 ft/d, and the measurement at 84.90 ft produced a borehole velocity of 1.2 ft/d. The remainder of the measurements produced velocities of less than 1 ft/d and tended to show an east-southeasterly flow direction; an exception was the measurement made in the middle of the open fracture at a depth of 80.91 ft, which had a flow direction to the southwest.

The open fracture in well FC-16 was estimated to have a hydraulic conductivity of 10 ft/d (based on estimates of zone transmissivity and thickness for the background geophysical logging listed in table 1). Solving for the corrected velocity, V_o, resulted in a ratio of

f_{cal} to f_{field} equal to 0.78,

which is the multiplication factor applied to the velocity measured in the borehole at a depth of 80.91 ft to give the seepage velocity in the aquifer. The resulting magnification factor of the borehole would be $1/0.78$, or 1.3 times the seepage velocity in the aquifer. For all other measurements in well FC-16, the correction factor was assumed to be 0.77 because of the extremely low hydraulic conductivity.

Momii and others (1993) have proposed that the simple analytical solution to seepage in a borehole is local magnitude of 3 times the formation flow. In a two-dimensional plane with unconsolidated sediments, measurements with the KVA flowmeter frequently converge on 2 times the formation flow. The correction of borehole velocity in fractured bedrock is based upon this assumption. With the KVA flowmeter, a cylinder of known permeability is placed in the horizontal-flow pathway, converting the fracture flow to porous flow to determine direction and rate. There must be impedance (resistance) of vertical flow by the packer "fuzz" on the top and bottom boundaries of the fracture or fractured zone. If the cavity exceeds the height of the packer, water can move vertically around the porous cylinder and the sensitivity of the probe is lowered to about one-twentieth of its normal capacity.

Acoustic Doppler Velocimeter

Measurements with the acoustic Doppler velocimeter (ADV) were made, August 30–September 2, 1999. Measurements were made at JPG on August 30 and 31. Flow in well JPG-5 was measured under ambient conditions, and flow in well JPG-2 was measured under ambient conditions and while pumping nearby well JPG-1. Measurements were made at Fort Campbell on September 1 and 2. Flow in wells FC-29, FC-15, and FC-16 were measured under ambient conditions.

The results of the ADV measurements are listed in tables 9 to 15, the depths of the measuring points are referenced to the top of casing. Each measurement typically required 10 minutes, which included carefully moving the probe to the next measurement depth and waiting for the water column to equilibrate or stabilize. Moving the probe in the JPG wells caused a noticeable displacement of the water level because of the low-permeability formations. In addition to the use of centralizers, a baffle/skirt made of foam and rubber was attached to the ADV to help isolate horizontal flow from vertical flow in the boreholes.

Before deployment of the ADV, a bailer was used to collect a sample of well water that was measured for temperature and fluid conductance. These measurements were entered into the acquisition software to calculate the speed of sound in the water. The ADV then was lowered into the water for a diagnostic check of probe alignment. Probe alignment is a quality-assurance check for proper probe function. When possible, a minimum of two to three flow measurements are taken in the cased part of the well. Because the water column in the casing is assumed to have no flow, measurements inside the casing can be used to determine an ambient background-noise level. The water levels in wells FC-15 and FC-16 were below the casing, so measurements were not made in the cased part of these two wells.

Point measurements of flow velocity and direction were made at the predetermined depths in the open hole. When moving from location to location, the ADV is moved as slowly as possible to minimize the effect on the ambient flows of ground water and the fluid column. After the probe is set at the desired depth, the flow velocities are monitored graphically; the data-acquisition software is used to verify that conditions have returned to ambient flow. Data acquisition is started when the standard deviation of the vertical flow falls below 0.002 ft/s. About 5 minutes of data were collected at each specified depth for processing. Field notes of data flags, average flows, and standard deviations also are recorded for each measurement location.

The presentation of flow data from the ADV is a combination of horizontal and vertical velocities. Horizontal velocities lie in a single horizontal plane and are described in terms of magnitude and direction. Vertical velocities are described in terms of magnitude and dip. Downward flow will have a negative value and dip between 91 and 180 degrees. Upward flow will have a positive value and a dip between 0 and 89 degrees. A dip of 90 degrees indicates horizontal flow with no vertical component. Bulk velocity is included in the tables of raw data for the ADV measurements. Bulk velocity is the vector sum of the horizontal velocity and vertical velocity and is the true flow magnitude of the borehole. The flow direction of the bulk velocity is the same as the horizontal velocity, and the dip is the angle that the bulk flow has from the vertical axis. The bulk velocity is not discussed in this report because the vertical velocities are suspected to be artificial rather than actual. The vertical velocities in some of the Fort Campbell wells only exist because the borehole has connected fractures with different hydraulic heads.

The velocity measurements made in well JPG-5 under ambient conditions are listed in table 9. The first three measurements were made in the casing to determine the background noise of the acoustic environment. The measurements in the casing implied horizontal and vertical flow in the water

Table 9. Borehole measurements of ground-water flow made with the acoustic Doppler velocimeter in well JPG-5, Jefferson Proving Ground, Indiana, August 30, 1999

[Depth is measured from top of casing; ft, foot; Flow direction is compass direction relative to true north; ft/s, foot per second; ft/d, foot per day; Dip is measured on a vertical plane of 0 to 180 degrees, where 90 degrees is horizontal; -, indicates vertical velocity is down; NA, measurement not adjusted; *, adjusted velocity is less than instrument resolution; NR, no remark; --, adjusted velocity is zero, direction is indeterminate; NT, time of measurement not available]

Depth (ft)	Time	Flow direction (degrees)	Horizontal velocity (ft/s)	Horizontal velocity (ft/d)	Vertical velocity (ft/s)	Bulk velocity (ft/s)	Dip (degrees)	Adjusted[a] horizontal velocity (ft/s)	Adjusted horizontal velocity (ft/d)	Flow direction (degrees)	Remarks
20.00	12:05	345	0.0011	95.0	-0.0055	0.0056	169	NA	NA	NA	In casing
30.00	12:12	326	.0010	86.4	-.0070	.0070	172	NA	NA	NA	In casing
34.00	12:19	43	.0005	43.2	-.0069	.0069	176	NA	NA	NA	In casing
39.00	12:26	181	.0006	51.8	-.0051	.0052	173	*0.0001	8.6	181	NR
39.50	12:34	298	.0004	34.6	-.0083	.0083	177	*0	0	--	NR
40.10	12:41	95	.0013	112	-.0074	.0075	170	.0008	69.1	95	NR
41.60	12:48	100	.0016	138	-.0079	.0080	169	.0011	95.0	100	NR
43.00	12:52	313	.0003	25.9	-.0049	.0049	177	*0	0	--	NR
44.10	13:01	339	.0014	121	-.0047	.0049	163	.0009	77.8	339	NR
45.00	13:08	224	.0009	77.8	-.0054	.0055	170	.0004	34.6	224	NR
40.10	NT	167	.0010	86.4	-.0079	.0080	173	.0005	43.2	167	Repeat
50.70	NT	306	.0012	104	-.0070	.0071	170	.0007	60.5	306	NR
51.30	NT	104	.0020	173	-.0079	.0081	166	.0015	130	104	NR
53.30	NT	338	.0018	156	-.0084	.0086	168	.0013	112	338	NR
54.50	NT	167	.0013	112	-.0091	.0092	172	.0008	69.1	167	NR
55.00	NT	188	.0003	25.9	-.0076	.0076	178	*0	0	--	NR
65.60	NT	248	.0004	34.6	-.0059	.0059	176	*0	0	--	NR
66.70	NT	185	.0010	86.4	-.0084	.0084	173	.0005	43.2	185	NR
70.20	NT	181	.0013	112	-.0071	.0072	169	.0008	69.1	181	NR
81.60	NT	196	.0038	328	-.0050	.0063	143	.0033	285	196	NR
83.50	NT	325	.0036	311	-.0057	.0068	148	.0031	268	325	NR
85.50	NT	223	.0005	43.2	-.0045	.0045	173	*0	0	--	NR
91.00	NT	27	.0005	43.2	-.0048	.0048	174	*0	0	--	NR
106.90	NT	105	.0508	4,389	.0038	.0510	86	.0503	4,346	105	NR
128.90	NT	323	.0346	2,989	.0079	.0354	77	.0341	2,946	323	NR
178.00	NT	229	.0012	104	-.0078	.0079	171	.0007	60.5	229	NR
67.60	NT	184	.0014	121	-.0093	.0094	171	.0009	77.8	184	NR
40.10	NT	250	.0012	104	-.0091	.0092	173	.0007	60.5	250	Repeat

[a]Adjusted horizontal velocity is reduced by 0.0005 foot per second, which was the background-noise level measured in the casing.

column inside the casing; however, there should be no actual flow inside the casing. The vertical-flow logging included a point measurement inside the casing under ambient conditions in which no flow was measured (fig. 10). It is possible that the ADV was measuring the movement of particles caused by thermal convections or a disturbed water column that was not completely stabilized.

The three measurements in the casing of well JPG-5 indicated the water column was becoming more stable with depth—at least the measurements detected less horizontal velocity with depth (table 9). Barring a crack in the casing, however, any detected flow would be the result of swirling. Therefore, the lower value of 0.0005 ft/s was considered to be the background-noise level of the velocity measurements, and it was subtracted from the horizontal velocities measured below the casing. Twenty-five velocity measurements made in well JPG-5 that have been adjusted for the background-noise level are listed in table 9. Six of the adjusted measurements resulted in zero horizontal velocity, which is reasonable given the low porosity and permeability of the bedrock. One of the adjusted measurements was greater than zero but below the lower limit of the instrument resolution of 0.0003 ft/s.

The ADV measured vertical flow in the downward direction in every well for the entire length of the well. The background vertical-flow logging indicated no ambient vertical flow (greater than 0.197 ft/min or 0.003 ft/s) in the wells at JPG and only ambient vertical flow between the fractures in the wells at Fort Campbell. The consistent measurement of the downward vertical flow is caused, at least in part, by sediment falling through the water column. The centralizer and baffle scraped material from the casing and borehole wall. A buildup of sediment consistently formed on the top of the ADV housing, indicating that sand and silt-sized sediments were falling through the water column. The vertical-velocity measurements are included with the ADV data but are not discussed here in detail. The vertical-velocity measurements are not considered to be indicative of actual ambient flow, and the other point-measurement methods do not have a vertical component to them for comparison.

The use of the ADV in wells without screens was considered a new application at the time of the data collection. Previous experience with the ADV always has been in screened wells in unconsolidated aquifers with high rates of ground-water flow. The low-flow conditions of the open bedrock wells at JPG and Fort Campbell may require a more rigorous threshold for data acquisition than was used. Once a data location is occupied, the flow velocities are graphically monitored; the acquisition software is used to verify that conditions have returned to steady flow. Data acquisition began when the standard deviation of the vertical flow fell below 0.002 ft/s. Perhaps this value of standard deviation needs to be lowered and the standard deviation of the horizontal flow needs to be monitored as well.

Measurements in well JPG-5 included all the depths measured with the KVA flowmeter plus additional measurements to a depth of 178.00 ft. Two repeat measurements were made at a depth of 40.10 ft, and the adjusted horizontal velocities were within the resolution (0.0003 ft/s or 25.9 ft/d) of the instrument (fig. 19). The adjusted horizontal velocities measured at a depth of 40.10 ft were 69.1, 43.2, and 60.5 ft/d (table 9). The flow directions were more variable, ranging from 95 to 167 to 250 degrees.

The horizontal velocities measured with the ADV in well JPG-5 were variable for magnitude and direction. No consistent flow direction was measured throughout the well, but several measurements indicated flow directions to the south at about 180 degrees and to the northwest at about 330 degrees. The highest velocities were measured below the water-producing zone determined by the vertical-flow logging. The measurements of apparently high velocities at depths of 81.60, 83.50, 106.90, and 128.90 ft have to be considered suspect, given that the vertical-flow logging did not detect contributing flow below a depth of 55 ft during pumping. The measurements at depths of 106.90 and 128.90 ft indicated extremely large values of horizontal flow and positive values of vertical flow—the only vertical flow in the upward direction measured in the study. It is not known what occurred at these depths to make the ADV record strong horizontal flows, whether actual or artificial.

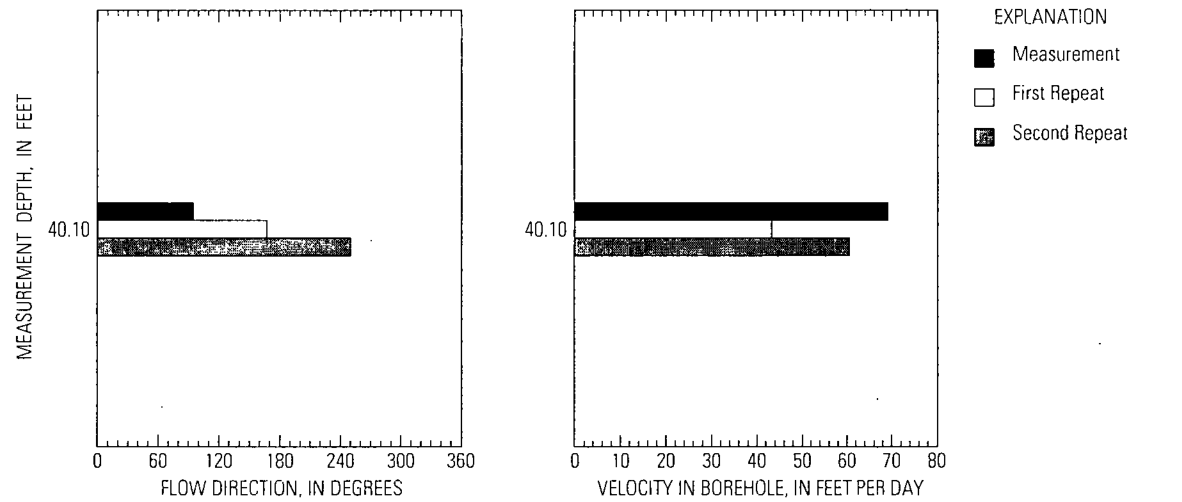


Figure 19. Flow directions and velocities for multiple measurements made with the acoustic Doppler velocimeter at a depth of 40.10 feet in well JPG-5, Jefferson Proving Ground, Indiana.

Measurements were made in well JPG-2 under ambient conditions and while pumping nearby well JPG-1. The measurements made in well JPG-2 under ambient conditions are listed in table 10. The first three measurements were made inside the casing to determine the background-noise level of the velocity measurements. The average horizontal velocity of the three measurements inside the casing was 0.0005 ft/s. Because determining a background-noise level is arbitrary, the average horizontal velocity in the casing (0.0005 ft/s) was used for consistency with the value used for well JPG-5.

Thirty velocity measurements made in well JPG-2 that were adjusted for the background-noise level by subtracting 0.0005 ft/s are listed in table 10. Measurements were made from depths of 41.75 to 138.10 ft. As in well JPG-5, several of the adjusted measurements resulted in velocities of 0 ft/d, and the measured horizontal velocities were variable for magnitude and direction. There was no consistent flow direction throughout the well; several measurements and repeat measurements had flow directions to the northwest around 310 to 340 degrees, similar to flow directions measured with the KVA flowmeter (tables 3 and 5). The highest values of horizontal velocity generally were measured in the producing zone from 45 to 65 ft, determined from the vertical-flow logging.

Repeat measurements were made at depths of 41.75, 48.66, 50.34, 50.53, and 54.02 ft (fig. 20). Some of the repeat measurements were made on the same day as the original measurement, but others were made on the following day (table 10). The two measurements at 41.75 ft had adjusted horizontal velocities within the resolution of the tool (43.2 and 17.3 ft/d) but the flow directions varied by 103 degrees (26 degrees and 283 degrees). The horizontal velocity of the repeat measurement at a depth of 48.66 ft was half the value of the original measurement (156 and 77.8 ft/d), but the two measurements produced fairly consistent flow directions to the northwest of 340 and 311 degrees. Four measurements were made at a depth of 50.34 ft, the fourth made just prior to the pumping on August 31 (table 11). The measurements yielded two pairs of horizontal velocities similar to each other but very different from the other pair (147, 51.8, 156, and 34.6 ft/d) (fig. 20). The first three measurements at a depth of 50.34 ft yielded

Table 10. Borehole measurements of ground-water flow made with the acoustic Doppler velocimeter in well JPG-2, Jefferson Proving Ground, Indiana, August 30–31, 1999

[Depth is measured from top of casing; ft, foot; Flow direction is compass direction relative to true north; ft/s, foot per second; ft/d, foot per day; Dip is measured on a vertical plane of 0 to 180 degrees, where 90 degrees is horizontal; -, indicates vertical velocity is down; NA, measurement not adjusted; *, adjusted velocity is less than instrument resolution; NR, no remark; --, adjusted velocity is zero, direction is indeterminate]

Depth (ft)	Time	Flow direction (degrees)	Horizontal velocity (ft/s)	Horizontal velocity (ft/d)	Vertical velocity (ft/s)	Bulk velocity (ft/s)	Dip (degrees)	Adjusted[a] horizontal velocity (ft/s)	Adjusted horizontal velocity (ft/d)	Flow direction (degrees)	Remarks
					Measurements made on August 30						
20.00	17:40	45	0.0005	43.2	-0.0004	0.0006	130	NA	NA	NA	In casing
27.00	17:48	353	.0007	60.5	-.0027	.0028	165	NA	NA	NA	In casing
34.00	17:54	283	.0003	25.9	-.0039	.0039	176	NA	NA	NA	In casing
41.75	18:00	26	.0010	86.4	-.0058	.0059	170	.0005	43.2	26	NR
41.75	18:05	283	.0007	60.5	-.0059	.0060	173	*.0002	17.3	283	Repeat
44.01	18:11	314	.0013	112	-.0047	.0049	164	.0008	69.1	314	NR
46.53	18:18	292	.0005	43.20	-.0057	.0057	175	*0	0	--	NR
48.66	18:25	340	.0023	199	-.0057	.0062	158	.0018	156	340	NR
50.34	18:33	312	.0022	190	-.0057	.0061	159	.0017	147	312	NR
53.48	18:44	256	.0017	147	-.0045	.0048	159	.0012	104	256	NR
54.02	18:53	336	.0016	138	-.0097	.0098	171	.0011	95.0	336	NR
55.51	18:59	297	.0018	156	-.0078	.0080	167	.0013	112	297	NR
57.38	19:07	300	.0026	225	-.0082	.0086	162	.0021	181	300	NR
58.38	19:14	340	.0003	25.9	-.0084	.0082	178	*0	0	--	NR
60.76	19:21	324	.0020	173	-.0080	.0083	166	.0015	130	324	NR
50.34	19:32	320	.0011	95.0	-.0084	.0085	173	.0006	51.8	320	Repeat

Table 10. Borehole measurements of ground-water flow made with the acoustic Doppler velocimeter in well JPG-2, Jefferson Proving Ground, Indiana, August 30–31, 1999—Continued

Depth (ft)	Time	Flow direction (degrees)	Horizontal velocity (ft/s)	Horizontal velocity (ft/d)	Vertical velocity (ft/s)	Bulk velocity (ft/s)	Dip (degrees)	Adjusted[a] horizontal velocity (ft/s)	Adjusted horizontal velocity (ft/d)	Flow direction (degrees)	Remarks
					Measurements made on August 31						
34.00	09:26	323	0.0010	86.4	-0.0037	0.0039	165	NA	NA	NA	In casing
48.66	09:34	311	.0014	121	-.0049	.0051	164	.0009	77.8	311	Repeat
50.34	09:41	331	.0023	199	-.0057	.0062	158	.0018	156	331	Repeat
54.02	09:49	3	.0007	60.5	-.0064	.0064	173	*.0002	17.3	3	Repeat
63.60	10:00	3	.0005	43.2	-.0073	.0073	176	*0	0	--	NR
69.60	10:08	352	.0014	121	-.0078	.0080	170	.0009	77.8	352	NR
74.80	10:16	250	.0003	25.9	-.0088	.0088	178	*0	0	--	NR
75.60	10:23	39	.0001	8.6	-.0083	.0083	179	*0	0	--	NR
77.10	10:30	71	.0009	77.8	-.0077	.0078	173	.0004	34.6	71	NR
83.10	10:39	59	.0006	51.8	-.0092	.0092	176	*.0001	8.6	59	NR
91.32	10:48	322	.0005	43.2	-.0093	.0094	177	*0	0	--	NR
91.80	10:55	29	.0006	51.8	-.0083	.0084	176	*.0001	8.6	29	NR
97.11	11:03	341	.0009	77.8	-.0044	.0045	168	.0004	34.6	341	NR
138.10	11:17	322	.0012	104	-.0087	.0087	172	.0007	60.5	322	NR
50.53	11:34	14	.0017	147	-.0096	.0097	170	.0012	104	14	NR
50.53	11:39	19	.0011	95.0	-.0088	.0089	173	.0006	51.8	19	Repeat
50.53	11:49	45	.0005	43.2	-.0091	.0091	177	*0	0	--	Repeat
50.53	11:54	26	.0007	60.5	-.0091	.0091	175	*.0002	17.3	26	Repeat

[a]Adjusted horizontal velocity is reduced by 0.0005 foot per second, which was the background-noise level measured in the casing.

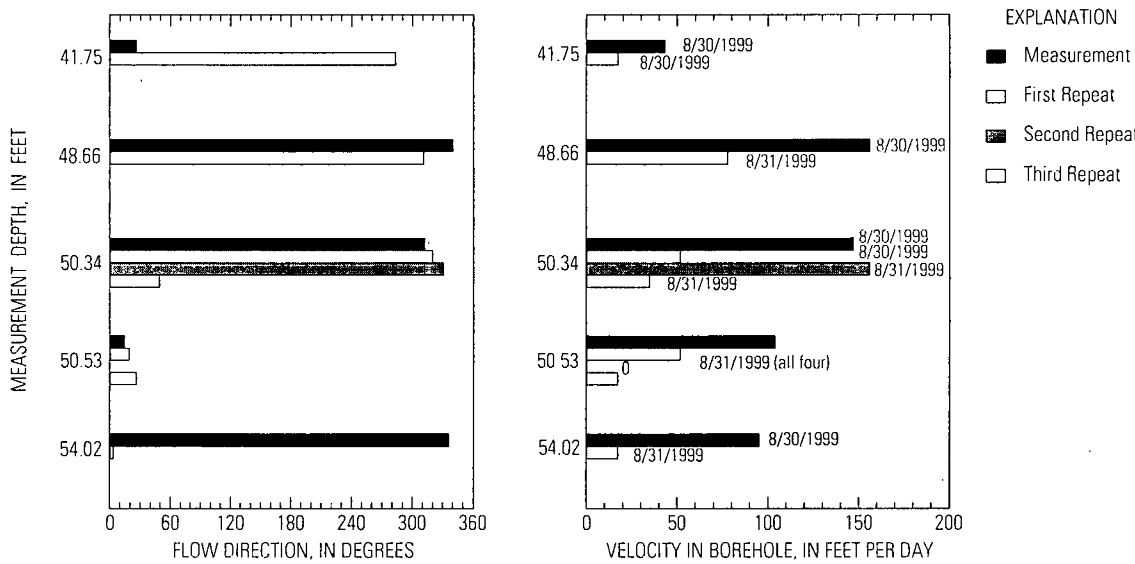


Figure 20. Flow directions and velocities for multiple measurements made with the acoustic Doppler velocimeter at selected depths in well JPG-2, Jefferson Proving Ground, Indiana.

consistent flow directions to the northwest of 312, 320, and 331 degrees, but the fourth measurement yielded a flow direction of 49 degrees.

Four measurements were made at a depth of 50.53 ft, yielding adjusted horizontal velocities that ranged from 0 to 104 ft/d (104, 51.8, 0, 17.3 ft/d) and flow directions from 14 to 26 degrees (14 degrees, 19 degrees, and 26 degrees). The multiple measurements at 50.34 ft and 50.53 ft show that the measured velocities and flow directions can vary substantially over a short distance along the borehole. The two measurements at a depth of 54.02 ft yielded substantially different horizontal velocities (95.0 and 17.3 ft/d), with flow directions that varied by only 27 degrees (336 degrees and 3 degrees).

After the measurements were completed for ambient conditions in well JPG-2, nearby well JPG-1 was pumped to induce ground-water flow to the pumped well. Thirty-five measurements made in well JPG-2 while pumping well JPG-1 (with the horizontal velocities adjusted for the background noise) are listed in table 11. The first 14 measurements are a time series for the depth of 50.34 ft. The first measurement of the time series was made under ambient conditions just prior to the pump being turned on. Repeat measurements were made at depths of 46.53, 48.66, 50.34, 53.48, and 58.38 ft (fig. 21). The measurements at a depth of 50.34 ft are the first five measurements during pumping from the time-series test. As with the measurements made under ambient conditions, the repeat measurements yielded velocities and flow directions that varied from the original measurements. The velocities tended to vary more than the flow directions (table 11).

The time-series measurements at a depth of 50.34 ft are shown in figure 22, and the drawdown curves for wells JPG-1 and JPG-2 are shown in figure 23, p. 56. Well JPG-1 was pumped at an average rate of 0.74 gal/min. The time-series measurements were made from 12:55 through 14:00; the pump in well JPG-1 was turned on at 13:00. The ADV did not detect a significant increase in horizontal velocity during the first hour of pumping (fig. 22). Three measurements in the time series had higher horizontal velocities than those measured

Table 11. Borehole measurements of ground-water flow made with the acoustic Doppler velocimeter in well JPG-2 while pumping nearby well JPG-1, Jefferson Proving Ground, Indiana, August 31, 1999

[Depth is measured from top of casing; ft, foot; Flow direction is compass direction relative to true north; ft/s, foot per second; ft/d, foot per day; Dip is measured on a vertical plane of 0 to 180 degrees, where 90 degrees is horizontal; -, indicates vertical velocity is down; *, adjusted velocity is less than instrument resolution; --, adjusted velocity is zero, direction is indeterminate; NR, no remark]

Depth (ft)	Time	Flow direction (degrees)	Horizontal velocity (ft/s)	Horizontal velocity (ft/d)	Vertical velocity (ft/s)	Bulk velocity (ft/s)	Dip (degrees)	Adjusted[a] horizontal velocity (ft/s)	Adjusted horizontal velocity (ft/d)	Flow direction (degrees)	Remarks
50.34	12:55	49	0.0009	77.8	-0.0096	0.0096	175	0.0004	34.6	49	Pump off
50.34	13:00	46	.0007	60.5	-.0096	.0096	176	*.0002	17.3	46	Pump on
50.34	13:05	53	.0007	60.5	-.0097	.0097	176	*.0002	17.3	53	Repeat
50.34	13:10	49	.0006	51.8	-.0096	.0096	176	*.0001	8.6	49	Repeat
50.34	13:15	51	.0008	69.1	-.0097	.0097	175	.0003	25.9	51	Repeat
50.34	13:20	34	.0010	86.4	-.0096	.0097	174	.0005	43.2	34	Repeat
50.34	13:25	38	.0008	69.1	-.0097	.0097	175	.0003	25.9	38	Repeat
50.34	13:30	32	.0008	69.1	-.0097	.0097	175	.0003	25.9	32	Repeat
50.34	13:35	7	.0009	77.8	-.0096	.0097	175	.0004	34.6	7	Repeat
50.34	13:40	29	.0010	86.4	-.0096	.0096	174	.0005	43.2	29	Repeat
50.34	13:45	116	.0009	77.8	-.0090	.0091	175	.0004	34.6	116	Repeat
50.34	13:50	354	.0006	51.8	-.0092	.0092	176	*.0001	8.6	354	Repeat
50.34	13:55	55	.0005	43.2	-.0095	.0095	177	*0	0	--	Repeat
50.34	14:00	81	.0011	95.0	-.0091	.0092	173	.0006	51.8	81	Repeat

Table 11. *Borehole measurements of ground-water flow made with the acoustic Doppler velocimeter in well JPG-2 while pumping nearby well JPG-1, Jefferson Proving Ground, Indiana, August 31, 1999—Continued*

Depth (ft)	Time	Flow direction (degrees)	Horizontal velocity (ft/s)	Horizontal velocity (ft/d)	Vertical velocity (ft/s)	Bulk velocity (ft/s)	Dip (degrees)	Adjusted[a] horizontal velocity (ft/s)	Adjusted horizontal velocity (ft/d)	Flow direction (degrees)	Remarks
48.66	14:05	41	0.0048	415	-0.0097	0.0108	153	0.0043	372	41	NR
48.66	14:10	18	.0021	181	-.0093	.0095	168	.0016	138	18	Repeat
48.66	14:15	37	.0013	112	-.0096	.0097	172	.0008	69.1	37	Repeat
46.53	14:25	33	.0016	138	-.0097	.0099	171	.0011	95.0	33	NR
46.53	14:30	53	.0015	130	-.0098	.0099	171	.0010	86.4	53	Repeat
44.01	14:45	146	.0009	77.8	-.0076	.0077	173	.0004	34.6	146	NR
53.48	14:55	78	.0008	69.1	-.0101	.0101	176	.0003	25.9	78	NR
53.48	15:00	32	.0017	147	-.0098	.0100	170	.0012	104	32	Repeat
54.02	15:10	17	.0015	130	-.0098	.0099	171	.0010	86.4	17	NR
57.38	15:20	30	.0018	156	-.0102	.0103	170	.0013	112	30	NR
58.38	15:30	45	.0020	173	-.0093	.0095	168	.0015	130	45	NR
60.76	15:40	10	.0023	199	-.0083	.0086	164	.0018	156	10	NR
63.60	15:50	48	.0007	60.5	-.0104	.0104	176	*.0002	17.3	48	NR
69.60	16:00	102	.0003	25.9	-.0091	.0092	178	*0	0	--	NR
74.80	16:10	35	.0008	69.1	-.0092	.0092	175	.0003	25.9	35	NR
75.60	16:20	55	.0010	86.4	-.0094	.0094	174	.0005	43.2	55	NR
77.10	16:30	41	.0010	86.4	-.0094	.0094	174	.0005	43.2	41	NR
138.10	16:45	341	.0012	104	-.0091	.0092	173	.0007	60.5	341	NR
139.20	16:54	337	.0008	69.1	-.0094	.0094	175	.0003	25.9	337	NR
58.38	17:08	49	.0015	130	-.0102	.0103	172	.0010	86.4	49	Repeat
58.38	17:13	33	.0008	69.1	-.0098	.0098	175	.0003	25.9	33	Repeat

[a]Adjusted horizontal velocity is reduced by 0.0005 foot per second, which was the background-noise level measured in the casing.

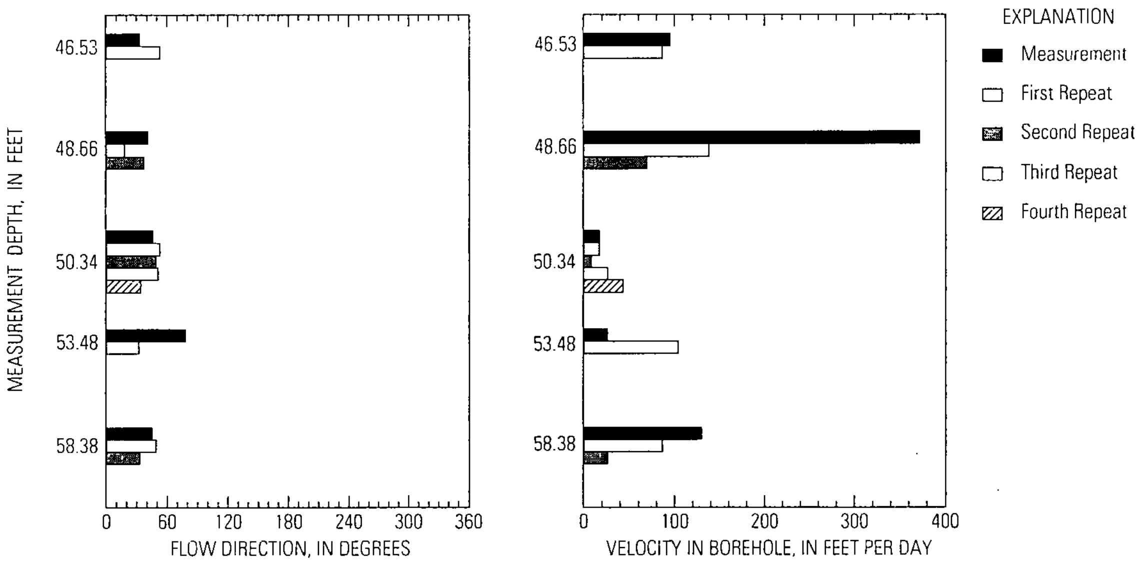


Figure 21. Flow directions and velocities for multiple measurements made with the acoustic Doppler velocimeter at selected depths in well JPG-2 while pumping nearby well JPG-1, Jefferson Proving Ground, Indiana.

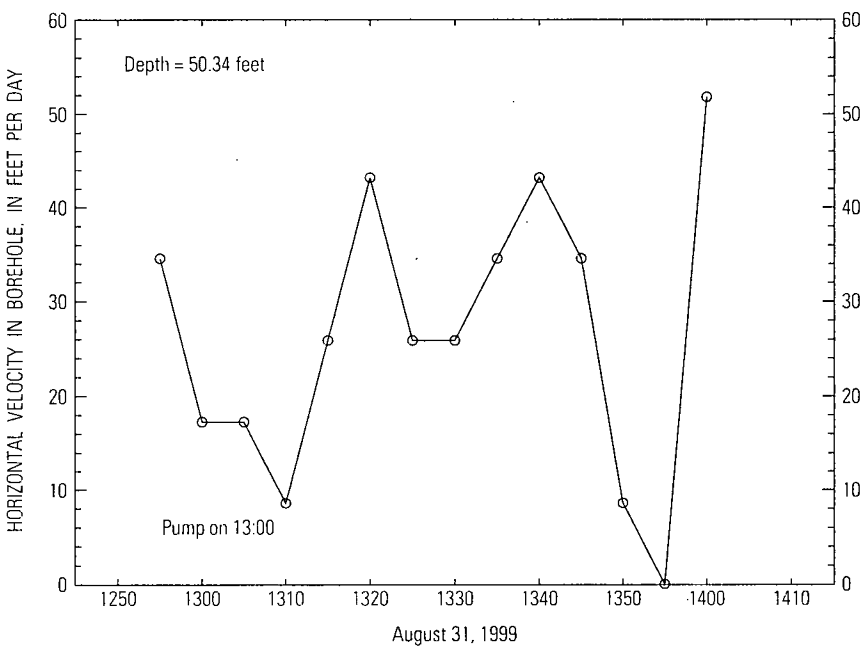


Figure 22. Time-series plot of velocity measurements made with the acoustic Doppler velocimeter at a depth of 50.34 feet in well JPG-2 while pumping well JPG-1, Jefferson Proving Ground, Indiana.

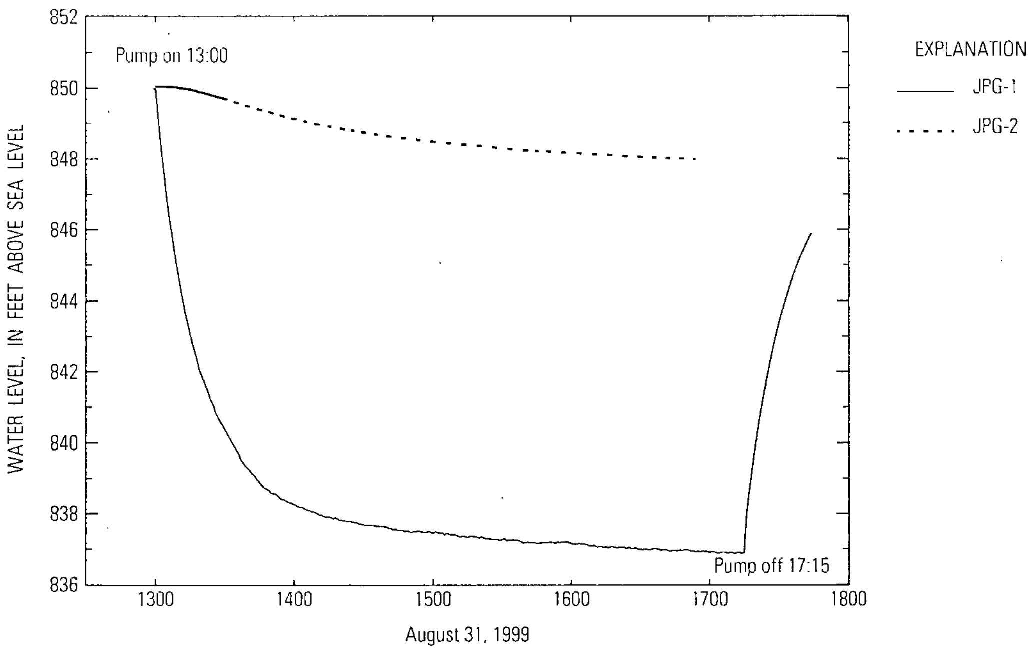


Figure 23. Drawdown curves for well JPG-2 and nearby well JPG-1, which was pumped at 0.74 gallon per minute, while measurements were made with the acoustic Doppler velocimeter in well JPG-2, Jefferson Proving Ground, Indiana.

under ambient conditions. After 1 hour of pumping well JPG-1, approximately 0.9 ft of drawdown in well JPG-2 (fig. 23) was measured. At the end of pumping, approximately 2.1 ft of drawdown in well JPG-2 was measured.

The depths at which measurements were made under ambient and pumping conditions are listed in table 12. The drawdown curves (fig. 23) show that a water-level difference of about 11 to 12 ft developed between the two wells during the pumping. The measured velocities in the borehole (adjusted for background noise) were slightly higher under pumping conditions than under ambient conditions, except for a few instances, but the average velocity while pumping was not appreciably higher. At some depths, the horizontal velocity during pumping was much lower than during ambient conditions. The average flow directions for ambient and pumped conditions indicate that the ADV did not record a shift in flow direction towards the pumped well. The average flow direction under ambient conditions was to the west at 265 degrees (table 12), with several readings from 300 to 352 degrees. The average flow direction during the pumping was to the northeast at 61 degrees. Average flow directions can be misleading because north is represented by two numbers—0 and 360 degrees.

The vertical velocities measured in the borehole increased during the pump test. It is uncertain if the increase in vertical velocity is actual and associated with the drawdown in well JPG-2. Increased downward velocities would imply that flow was leaving well JPG-2 below the measurement point. A measurement was not made near the bottom of the well to determine if the downward velocity reversed. Because of the time variable, differences in the directions and velocities in table 12 were not computed; however, the data are presented to show the relative differences and the general trends.

The highest horizontal velocity measured during the pumping was 372 ft/d (41 degrees) at a depth of 48.66 ft. One of the higher velocities under ambient conditions also was measured at a depth of

Table 12. Borehole measurements of ground-water flow made with the acoustic Doppler velocimeter in well JPG-2 for ambient conditions and while pumping nearby well JPG-1, adjusted for the background noise, Jefferson Proving Ground, Indiana, August 30–31, 1999

[Depth is measured from top of casing; ft, foot; Flow direction is compass direction relative to true north; ft/d, foot per day; ft/s, foot per second; -, indicates vertical velocity is down; --, adjusted velocity is zero, direction is indeterminate; *, adjusted velocity less than instrument resolution; NM, no measurement]

Depth (ft)	Flow direction while ambient (degrees)	Flow direction while pumping (degrees)	Adjusted[a] horizontal velocity while ambient (ft/d)	Adjusted horizontal velocity while pumping (ft/d)	Vertical velocity while ambient (ft/s)	Vertical velocity while pumping (ft/s)	Elapsed pumping time (minutes)
44.01	314	146	69.1	34.6	-0.0047	-0.0076	105
46.53	--	33	*0	95.0	-.0057	-.0097	85
46.53	NM	53	NM	86.4	NM	-.0098	90
48.66	340	41	156	372	-.0057	-.0097	65
48.66	311	18	77.8	138	-.0049	-.0093	70
48.66	NM	37	NM	69.1	NM	-.0096	75
50.34	253[b]	72[c]	97.4[b]	25.9[c]	-.0074[b]	-.0095[c]	Varies
53.48	256	78	104	25.9	-.0045	-.0101	115
53.48	NM	32	NM	104	NM	-.0098	120
54.02	336	17	95.0	86.4	-.0097	-.0098	130
54.02	3	NM	*17.3	NM	-.0064	NM	NM
57.38	300	30	181	112	-.0082	-.0102	140
58.38	--	45	*0	130	-.0084	-.0093	150
58.38	NM	49	NM	86.4	NM	-.0102	248
58.38	NM	33	NM	25.9	NM	-.0098	253
60.76	324	10	130	156	-.0080	-.0083	160
63.60	--	48	*0	*17.3	-.0073	-.0104	170
69.60	352	--	77.8	*0	-.0078	-.0091	180
74.80	--	35	*0	25.9	-.0088	-.0092	190
75.60	--	55	*0	43.2	-.0083	-.0094	200
77.10	71	41	34.6	43.2	-.0077	-.0094	210
138.10	322	341	60.5	60.5	-.0087	-.0091	225
Average	**265**	**61**	**65**	**83**	**-.0072**	**-.0095**	not averaged

[a]Adjusted horizontal velocity is reduced by 0.0005 foot per second, which was the background-noise level measured in the casing.

[b]Average of four velocity and direction measurements at a depth of 50.34 feet, while ambient.

[c]Average of 13 velocity measurements and 12 direction measurements at a depth of 50.34 feet, while pumping well JPG-1 (table 11).

48.66 ft (156 ft/d, 340 degrees). The most notable increases in velocity from ambient to pumping conditions were measured at depths of 46.53, 48.66, 58.38, 74.80, and 75.60 ft (table 12).

Although several velocities measured with the ADV were higher during the pumping, the measurements did not show the anticipated effect of flow directions towards the pumping well. The pumping time probably was insufficient to cause a consistent increase in velocity and to cause a complete change in flow direction towards the pumping well. The response in the low-permeability bedrock probably was delayed more than in a highly permeable sand aquifer or in bedrock with open fractures. Even though well JPG-2 was in hydraulic connection with well JPG-1, it is possible that some of the tested zones were not.

Borehole measurements of ground-water flow were made in the wells at Fort Campbell on September 1 and 2, 1999. The depths at which measurements were made in well FC-29 are listed in table 13. The first three measurements, at depths of 42.50 and 43.50 ft, were made inside the casing to determine the background-noise level of the velocity measurements. A value of 0.0014 ft/s was used as the background-noise level because it was measured at each of the depths tested inside the casing. This value is much higher than the velocity measured inside the casing of the JPG wells. The higher background-noise velocity in the Fort Campbell wells may be related to the larger casing diameter. The relatively high background velocity also may be affected by the shallowness of the measurements—the static water level was at 39.5 ft for the ADV measurements, and the bottom of casing was at 44.0 ft.

Measurements of horizontal velocity in well FC-29 were adjusted for the background-noise level by subtracting 0.0014 ft/s (table 13). Many of the adjusted measurements resulted in horizontal velocities of 0 ft/d. The highest measured velocities are at the two open fractures near depths of 67.20 and 91.42 ft. The background vertical-flow logging indicated there was about 0.15 gal/min of ambient vertical flow from the upper fracture down to the lower fracture (fig. 11). The ADV detected strong downward vertical velocities throughout the borehole, even above the upper fracture and below the lower fracture, which suggests that the apparent vertical velocities were affected by debris falling through the water column. The highest vertical velocity was measured at a depth of 90.76 ft at the top edge of the lower fracture where flow was exiting the borehole (fig. 11).

Only one measurement above the upper fracture had a positive horizontal velocity after being adjusted for the background noise. A horizontal velocity of 51.8 ft/d, with a flow direction of 116 degrees, was measured at a depth of 53.92 ft (table 13). A repeat measurement at this depth had a horizontal velocity of zero. None of the measurements below the lower fracture had a positive horizontal velocity after being adjusted for the background noise.

The ADV measured apparent horizontal velocity at the upper and lower fractures. These apparent horizontal velocities, however, may be affected by the vertical flow from the upper fracture to the lower fracture. It is possible that true horizontal flow could not occur across the borehole between the two fractures if there was enough vertical head gradient to drive flow from one fracture to the other. The measured horizontal velocities at the fractures may be the rate at which water exited the upper fracture and entered the lower fracture, rather than being true horizontal flow across the borehole. The three measurements that detected flow at the upper fracture show a flow direction to the north that ranged from 0 to 9 degrees (table 13), indicating that flow entered the borehole from the south. Three of the measurements at the lower fracture had flow directions to the west-northwest (256 degrees, 320 degrees, and 321 degrees), indicating that the flow exited the borehole to the west-northwest. The fourth measurement that detected flow at the lower fracture had a flow direction of 19 degrees, but the adjusted velocity was below the tool resolution and may not be valid.

The ADV was used with a baffle/skirt to suppress vertical flow and isolate the horizontal flow. It is uncertain how effective the baffle/skirt was in reducing or eliminating the vertical flow between the fractures. While measurements were made at the upper fracture, the baffle/skirt was above the

Table 13. Borehole measurements of ground-water flow made with the acoustic Doppler velocimeter in well FC-29, Fort Campbell, Kentucky, September 1, 1999

[Depth is measured from top of casing; ft, foot; Flow direction is compass direction relative to true north; ft/s, foot per second; ft/d, foot per day; Dip is measured on a vertical plane of 0 to 180 degrees, where 90 degrees is horizontal; -, indicates vertical velocity is down; NA, measurement not adjusted; *, adjusted velocity is less than instrument resolution; --, adjusted velocity is zero, direction is indeterminate; NR, no remark]

Depth (ft)	Time	Flow direction (degrees)	Horizontal velocity (ft/s)	Horizontal velocity (ft/d)	Vertical velocity (ft/s)	Bulk velocity (ft/s)	Dip (degrees)	Adjusted[a] horizontal velocity (ft/s)	Adjusted horizontal velocity (ft/d)	Flow direction (degrees)	Remarks
42.50	10:02	105	0.0014	121	-0.0058	0.0059	167	NA	NA	NA	In casing
43.50	10:06	135	.0014	121	-.0062	.0063	167	NA	NA	NA	In casing
43.50	10:11	134	.0016	138	-.0052	.0054	163	NA	NA	NA	In casing
50.37	10:20	108	.0012	104	-.0072	.0073	170	*0	0	--	NR
53.92	10:30	116	.0020	173	-.0069	.0072	164	.0006	51.8	116	NR
65.96	10:41	82	.0009	77.8	-.0077	.0077	173	*0	0	--	.2 ft above fracture
66.16	10:49	84	.0007	60.5	-.0071	.0071	175	*0	0	--	Edge of fracture
66.30	10:57	116	.0005	43.2	-.0075	.0076	176	*0	0	--	Fracture
66.60	11:06	9	.0023	199	-.0074	.0077	163	.0009	77.8	9	Fracture
66.90	11:16	0	.0032	276	-.0084	.0090	159	.0018	156	0	Fracture
67.20	11:24	1	.0017	147	-.0064	.0066	165	.0003	25.9	1	Middle of fracture
67.50	11:34	88	.0013	112	-.0080	.0081	171	*0	0	--	Fracture
67.80	11:43	81	.0010	86.4	-.0087	.0088	174	*0	0	--	Fracture
68.06	11:51	46	.0012	104	-.0096	.0097	173	*0	0	--	Edge of fracture
68.27	11:59	52	.0012	104	-.0092	.0092	172	*0	0	--	.2 ft below fracture
70.00	12:12	332	.0010	86.4	-.0066	.0067	171	*0	0	--	NR
79.75	12:27	174	.0011	95.0	-.0041	.0043	165	*0	0	--	NR
90.76	12:39	256	.0023	199	-.0121	.0123	169	.0009	77.8	256	Edge of fracture
91.12	12:49	320	.0037	320	-.0093	.0100	158	.0023	199	320	Fracture
91.42	12:58	19	.0015	130	-.0086	.0087	170	*.0001	8.6	19	Middle of fracture
91.72	13:07	321	.0017	147	-.0076	.0078	167	.0003	25.9	321	Fracture
92.06	13:15	3	.0014	121	-.0088	.0089	171	*0	0	--	Edge of fracture
95.20	13:25	24	.0011	95.0	-.0092	.0092	173	*0	0	--	NR
102.70	13:35	324	.0002	17.3	-.0093	.0093	178	*0	0	--	NR
115.00	13:46	351	.0011	95.0	-.0086	.0087	173	*0	0	--	NR
68.27	14:02	355	.0011	95.0	-.0104	.0105	174	*0	0	--	Repeat
65.96	14:17	69	.0014	121	-.0085	.0086	171	*0	0	--	Repeat
53.92	14:32	295	.0014	121	-.0094	.0095	172	*0	0	--	Repeat

[a]Adjusted horizontal velocity is reduced by 0.0014 foot per second, which was the background-noise level measured in the casing.

fracture where it would not block the vertical flow. While measurements were made below the upper fracture, the baffle/skirt would have been in position to block or reduce the vertical flow moving down the borehole to the lower fracture.

The depths at which measurements were made in well FC-15 are listed in table 14. No measurements were made inside the casing because the water level was below the bottom of casing. Static water level was at 90.8 ft below the top of casing. Measurements inside the casing at the other wells indicate that the ADV consistently measured background noise as horizontal velocity; therefore, the measurements in well FC-15 needed to be adjusted even though there was no measurement of background noise. To be consistent, the background-noise level of 0.0014 ft/s measured in well FC-29 was applied to the horizontal velocities measured in well FC-15. Wells FC-29 and FC-15 have the same diameter and the same type of casing.

Well FC-15 has three open fractures that intersect the borehole. Measurements were made at the middle of each of these fractures with the ADV. The fractures are centered at depths of 128.45, 143.52, and 154.78 ft (table 14). These depths were determined by visual observation with a downhole camera. The June 1999 vertical-flow logging measured about 0.4 gal/min of ambient vertical flow from the upper fracture down to the second fracture and about 0.08 gal/min from the lower fracture up to the second fracture (fig. 12). As in well FC-29, the horizontal velocities measured with the ADV may be affected by the vertical flow between the fractures. It is uncertain how effective the baffle/skirt device was in suppressing the vertical flow.

Measurements of horizontal velocity in well FC-15 were adjusted for the background-noise level by subtracting 0.0014 ft/s (table 14). Most of the adjusted measurements result in zero horizontal velocity because of the large assumed value of background noise. The highest measured velocity was at the second fracture, at a depth of 143.52 ft. The adjusted horizontal velocity at this depth was 216 ft/d, with a flow direction of 118 degrees. Repeat measurements were made at depths of 143.38 and 128.45 ft. Both repeat measurements recorded higher horizontal velocities than the original measurements, which were both 0 ft/d. The adjusted horizontal velocity for the repeat measurement at 128.45 ft was 25.9 ft/d, with a flow direction of 259 degrees. The adjusted horizontal velocity at 143.38 ft was 181 ft/d, with a flow direction of 131 degrees. The measurements at 143.38 ft were at the upper edge of the second fracture. The flow direction of 131 degrees is consistent with the flow direction measured at 143.52 ft, the middle of the second fracture.

The depths at which measurements were made in well FC-16 are listed in table 15. No measurements were made inside the casing because the water level was at 54.6 ft below the top of casing, and the bottom of casing was at 47.2 ft. To be consistent with the other wells at Fort Campbell, the background-noise level of 0.0014 ft/s measured in well FC-29 was subtracted from the horizontal velocities measured in well FC-16.

Measurements of horizontal velocity in well FC-16 were adjusted for the background-noise level by subtracting 0.0014 ft/s (table 15). With the exception of the repeat measurements, all of the measurements had westerly flow directions, ranging from southwest (245 degrees) to northwest (293 degrees). Repeat measurements were made at depths of 68.95, 84.90, and 130.90 ft (fig. 24). The two measurements at 68.95 ft had comparable horizontal velocities within the resolution of the tool (17.3 and 34.6 ft/d) but the flow directions were not comparable (245 degrees and 359 degrees). The two measurements at 84.90 ft had comparable horizontal velocities of 8.6 and 17.3 ft/d, but the flow directions were not comparable (255 degrees and 40 degrees). The repeat measurement at 130.90 ft had an adjusted horizontal velocity of 0 ft/d, but the original measurement had a horizontal velocity of 95 ft/d.

Measurements were made at the upper and lower edges of the open fracture in well FC-16. The top edge of the fracture was at a depth of 80.75 ft, and the bottom edge was at a depth of 81.06 ft (table 15). These depths are based on visual observations with the downhole camera. The measurement at the middle of the open fracture, at a depth of 80.91 ft, had an adjusted horizontal velocity of 0 ft/d. The adjusted horizon-

Table 14. Borehole measurements of ground-water flow made with the acoustic Doppler velocimeter in well FC-15, Fort Campbell, Tennessee, September 2, 1999

[Depth is measured from top of casing; ft, foot; Flow direction is compass direction relative to true north; ft/s, foot per second; ft/d, foot per day; Dip is measured on a vertical plane of 0 to 180 degrees, where 90 degrees is horizontal; -, indicates vertical velocity is down; *, adjusted velocity is less than instrument resolution; --, adjusted velocity is zero, direction is indeterminate; NR, no remark]

Depth (ft)	Time	Flow direction (degrees)	Horizontal velocity (ft/s)	Horizontal velocity (ft/d)	Vertical velocity (ft/s)	Bulk velocity (ft/s)	Dip (degrees)	Adjusted[a] horizontal velocity (ft/s)	Adjusted horizontal velocity (ft/d)	Flow direction (degrees)	Remarks
96.82	12:30	288	0.0022	190	-0.0061	0.0064	160	0.0008	69.1	288	NR
104.90	12:39	298	.0016	138	-.0082	.0083	169	*.0002	17.3	298	NR
114.63	12:48	315	.0004	34.6	-.0002	.0004	121	*0	0	--	NR
116.27	12:56	215	.0020	173	-.0045	.0049	156	.0006	51.8	215	NR
124.41	13:06	336	.0011	95.0	-.0054	.0056	169	*0	0	--	NR
128.00	13:14	315	.0012	104	-.0017	.0021	146	*0	0	--	.2 ft above fracture
128.20	13:22	151	.0004	34.6	-.0007	.0008	29	*0	0	--	Edge of fracture
128.45	13:29	222	.0005	43.2	-.0002	.0005	112	*0	0	--	Middle of fracture
128.70	13:36	270	.0012	104	-.0046	.0047	166	*0	0	--	Edge of fracture
128.90	13:43	192	.0018	156	-.0026	.0031	146	.0004	34.6	192	.2 ft below fracture
130.10	13:50	309	.0013	112	-.0018	.0022	144	*0	0	--	NR
143.38	14:01	128	.0011	95.0	-.0017	.0020	147	*0	0	--	Edge of fracture
143.52	14:07	118	.0039	337	-.0040	.0056	135	.0025	216	118	Middle of fracture
143.65	14:14	272	.0009	77.8	-.0041	.0042	167	*0	0	--	Edge of fracture
150.77	14:22	57	.0012	104	-.0044	.0046	165	*0	0	--	NR
154.25	14:29	305	.0006	51.8	-.0047	.0047	173	*0	0	--	NR
154.55	14:36	86	.0012	104	-.0039	.0041	163	*0	0	--	Edge of fracture
154.78	14:43	258	.0012	104	-.0012	.0017	135	*0	0	--	Middle of fracture
155.00	14:51	270	.0015	130	-.0019	.0024	141	*0	0	--	Edge of fracture
155.30	14:56	206	.0013	112	-.0052	.0054	166	*0	0	--	.3 ft below fracture
143.38	15:10	131	.0035	302	-.0040	.0053	139	.0021	181	131	Repeat
128.45	15:18	259	.0017	147	-.0151	.0152	174	.0003	25.9	259	Repeat

[a]Adjusted horizontal velocity is reduced by 0.0014 foot per second, which was the assumed background-noise level measured in the casing.

Table 15. Borehole measurements of ground-water flow made with the acoustic Doppler velocimeter in well FC-16, Fort Campbell, Kentucky, September 1, 1999

[Depth is measured from top of casing; ft, foot; Flow direction is compass direction relative to true north; ft/s, foot per second; ft/d, foot per day; Dip is measured on a vertical plane of 0 to 180 degrees, where 90 degrees is horizontal; -, indicates vertical velocity is down; *, adjusted velocity is less than instrument resolution; --, adjusted velocity is zero, direction is indeterminate; NR, no remark]

Depth (ft)	Time	Flow direction (degrees)	Horizontal velocity (ft/s)	Horizontal velocity (ft/d)	Vertical velocity (ft/s)	Bulk velocity (ft/s)	Dip (degrees)	Adjusted[a] horizontal velocity (ft/s)	Adjusted horizontal velocity (ft/d)	Flow direction (degrees)	Remarks
68.95	16:18	245	0.0016	138	-0.0072	0.0074	168	*0.0002	17.3	245	NR
78.50	16:28	266	.0019	164	-.0072	.0075	166	.0005	43.2	266	NR
80.46	16:35	262	.0017	147	-.0071	.0073	166	.0003	25.9	262	.3 ft above fracture
80.75	16:42	252	.0017	147	-.0076	.0078	168	.0003	25.9	252	Edge of fracture
80.91	16:46	244	.0006	51.8	-.0075	.0075	175	*0	0	--	Middle of fracture
81.06	16:53	265	.0023	199	-.0074	.0078	163	.0009	77.8	265	Edge of fracture
81.36	16:59	285	.0018	156	-.0079	.0081	167	.0004	34.6	285	.3 ft below fracture
84.90	17:06	255	.0015	130	-.0077	.0078	169	*.0001	8.6	255	NR
97.30	17:15	264	.0018	156	-.0077	.0079	167	.0004	34.6	264	NR
102.30	17:23	269	.0022	190	-.0074	.0077	164	.0008	69.1	269	NR
104.83	17:30	284	.0009	77.8	-.0064	.0064	172	*0	0	--	NR
130.90	17:42	261	.0025	216	-.0076	.0080	162	.0011	95.0	261	NR
137.30	17:50	293	.0030	259	-.0042	.0052	144	.0016	138	293	NR
147.65	17:58	262	.0025	216	-.0082	.0086	163	.0011	95.0	262	NR
157.05	18:06	256	.0020	173	-.0082	.0084	166	.0006	51.8	256	NR
130.90	18:20	160	.0010	86.4	-.0087	.0088	174	*0	0	--	Repeat
84.90	18:32	40	.0016	138	-.0082	.0084	169	*.0002	17.3	40	Repeat
68.95	18:41	359	.0018	156	-.0115	.0117	171	.0004	34.6	359	Repeat

[a]Adjusted horizontal velocity is reduced by 0.0014 foot per second, which was the assumed background-noise level measured in the casing.

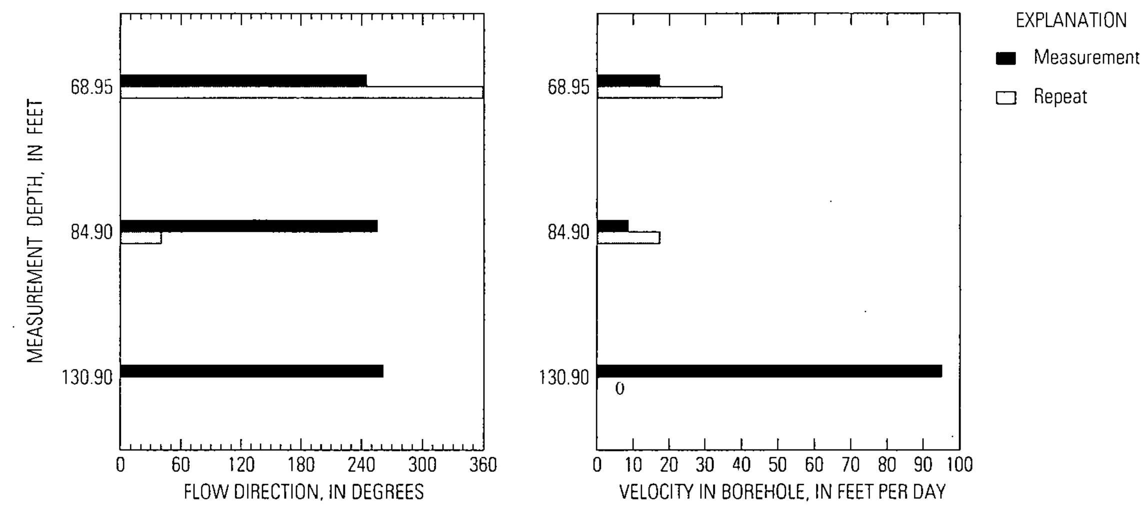


Figure 24. Flow directions and velocities for two measurements made with the acoustic Doppler velocimeter at selected depths in well FC-16, Fort Campbell, Kentucky.

tal velocity at the upper edge of the fracture was 25.9 ft/d, and the adjusted horizontal velocity at the lower edge was 77.8 ft/d. These two measurements at the fracture had comparable flow directions of 252 and 265 degrees. The highest value of adjusted horizontal velocity was 138 ft/d, measured at a depth of 137.30 ft.

Colloidal Borescope

Measurements with the colloidal borescope were made September 18–24, 1999. Measurements were made at JPG, September 18–20 (fig. 6). Well JPG-5 was tested under ambient conditions; well JPG-2 was tested under ambient conditions and while pumping nearby well JPG-1. Measurements were made at Fort Campbell, September 21–24 (fig. 7). Wells FC-29, FC-15, and FC-16 were tested under ambient conditions. Measurements with the colloidal borescope were made at the depths tested previously with the KVA flowmeter; if time permitted, additional depths were tested based on observations during the field tests or on results of the hydrophysical logging conducted during the same time period. A rubber disc was attached to the colloidal borescope to act as a baffle to help isolate horizontal flow from vertical flow in the borehole (fig. 3b).

The results of the colloidal borescope measurements are listed in tables 16 to 22; the depths of the measuring points are referenced to the top of casing. Only a few measurements in each well yielded reliable flow directions that indicate ground water is flowing horizontally from the formation, through the well, and back into the formation. According to Kearl (1997), these types of results indicate preferential flow zones such as fractures or permeable zones within the surrounding geologic formation.

Data for most of the measurements indicated swirling or nondirectional flow, characteristic of low- or no-flow zones where there is no continuous hydraulic connection between the well and the surrounding formation (Kearl, 1997). In zones with swirling flow, it is not possible to obtain a reliable measurement of ground-water velocity and flow direction. The data are useful, however, for indicating zones of low permeability relative to adjacent preferential flow zones. Swirling-flow zones are identified on the basis of continuous change in the flow direction, a steady decrease in velocity, or a high vertical-flow component observed during the measurement but not indicated by the data plot.

The data-acquisition software allows for continuous graphing of velocity and direction; therefore, it is evident if the borescope is positioned at a depth where the velocity and direction are consistent. At such depths, the time span of data collection usually was extended to acquire numerous measurements over 1 to 2 hours. At depths where there was apparent swirling flow, the data collection usually was stopped after about 15 minutes and the tool was moved to the next position to be measured.

Graphs of the velocity and direction data similar to those published in Kearl (1997) can be stored and printed for later use. Graphs for measurements considered to have reliable flow directions are included with the discussion of each test well. The average velocity and direction are based on all the data points, not just data that plot on the obvious trend lines. The graphs of velocity and direction data list the number of data points collected for each measurement, along with the average direction and velocity. The time axis is labeled as hours/minutes/seconds. In the early part of the measurements, flow directions and velocities commonly show more variability than after the borescope has been in place for some time. This variability is caused by moving the instrument into position at the depth to be measured, which causes a disturbance to the flow field and water column. In reliable flow zones, this initial disturbance to the flow field quickly dissipates and the ambient ground-water flow dominates the observed flow in the borehole.

The depths at which measurements were made in well JPG-5 are listed in table 16. Most of the measurements were concentrated in the depth range of 40 to 55 ft, which was determined to be the water-producing zone by the June 1999 vertical-flow logging. Several measurements were made in the lower part of the well, from 178 to 198 ft. These measurement depths were selected on the basis of preliminary results from the hydrophysical logging, which determined that there was a low rate of horizontal flow near the bottom of the well. Hydrophysical logging was completed in well JPG-5 a few days prior to the colloidal borescope measurements. The static water level in well JPG-5 for the colloidal borescope measurements was 12.4 ft below the top of casing.

Table 16. Borehole measurements of ground-water flow made with the colloidal borescope in well JPG-5, Jefferson Proving Ground, Indiana, September 18–19, 1999

[Depth is measured from top of casing; ft, foot; Flow direction is compass direction relative to true north; μm/s, micrometers per second; ft/d, foot per day]

Depth (ft)	Flow direction (degrees)	Velocity in borehole (μm/s)	Velocity in borehole (ft/d)
39.00	150	125	35
39.50	123	158	44
39.80	197	232	65
40.10[a]	161	312	87
40.60	219	289	81
41.10	182	356	100
41.60	258	503	141
43.00	198	469	131
44.10	143	521	146
45.00	142	444	124
50.70	170	461	129
51.30	210	481	135
53.30	221	371	104
60.80	179	247	69
178.00[a]	245	190	53
180.00	288	504	141
185.00	226	185	52
190.00	270	193	54
195.00[a]	242	137	38
198.00	211	106	30

[a]Measurement at this depth was determined to have consistent flow.

Most of the measurements yielded swirling, nondirectional flow, which suggests that the test zones were adjacent to low-permeable rock. Three measurements, at depths of 40.10, 178.00, and 195.00 ft yielded relatively consistent flow. At a depth of 40.10 ft, the average velocity in the borehole was 87 ft/d (312 μm/s), with an average flow direction of 161 degrees (fig. 25). The measurement at a depth of 178.00 ft yielded an average velocity

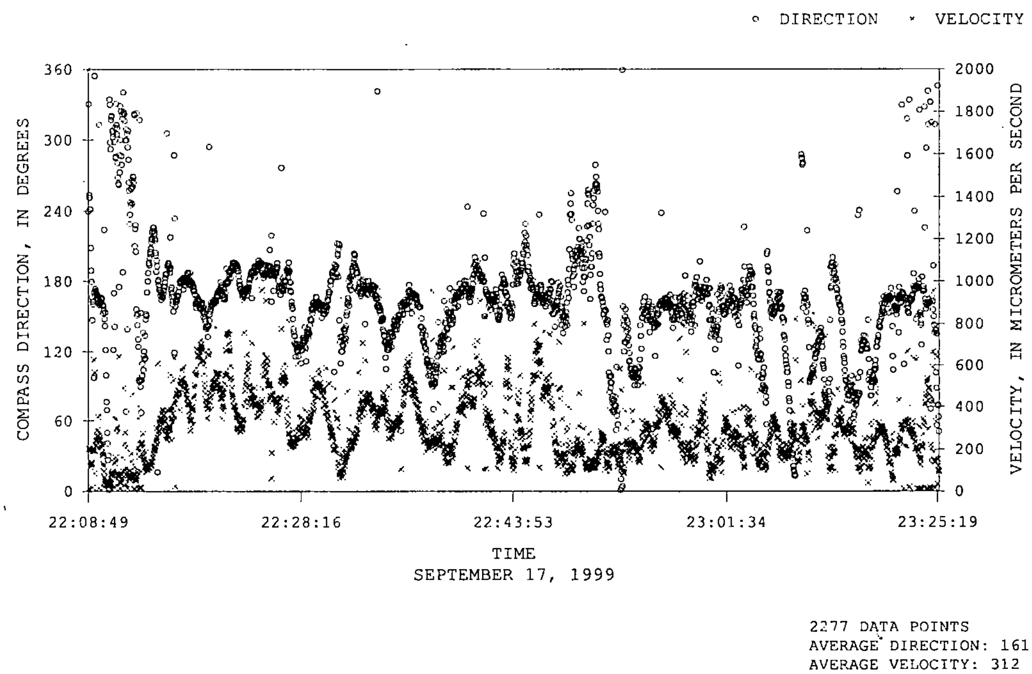


Figure 25. Colloidal borescope measurement at 40.10 feet in well JPG-5, Jefferson Proving Ground, Indiana.

of 53 ft/d, with an average flow direction of 245 degrees (fig. 26). Definite trends for the velocity and the direction are indicated, even though there are numerous data points for each scattered across the plot (fig. 26). If all of the scattered data and the data for the first 10 minutes are ignored, best-fit lines through the data would yield an average velocity close to 28 ft/d (100 μm/s) and an average flow direction of 260 degrees. The measurement at a depth of 195.00 ft yielded an average velocity of 38 ft/d and an average flow direction of 242 degrees (fig. 27).

The relative variability of each measurement can be seen by the flatness of the data line in each graph—more oscillations of the line indicate more variability. An example data graph of a uniform measurement with little variability in direction or velocity is shown in Kearl (1997, p. 329). An example data graph for a measurement from this study with swirling, nondirectional flow is shown in figure 28. In this graph, neither the direction or velocity data plot on a line for the 14 minutes the of data collection.

The depths at which measurements were made in well JPG-2 under ambient conditions are listed in table 17 (p. 69). The static water level in well JPG-2 was 17.0 ft below the top of casing during these measurements. Most of the measurements yielded swirling, nondirectional flow. Three measurements, at depths of 46.53, 48.66, and 58.38 ft, yielded relatively consistent velocities, with a moderate amount of directional variability. At a depth of 46.53 ft, the average velocity in the borehole was 54 ft/d, with an average flow direction of 146 degrees (fig. 29). The measurement at a depth of 48.66 ft yielded similar results, with an average velocity of 54 ft/d and an average flow direction of 152 degrees (fig. 30, p. 68). The measurement at a depth of 58.38 ft yielded an average velocity of 50 ft/d and an average flow direction of 202 degrees (fig. 31).

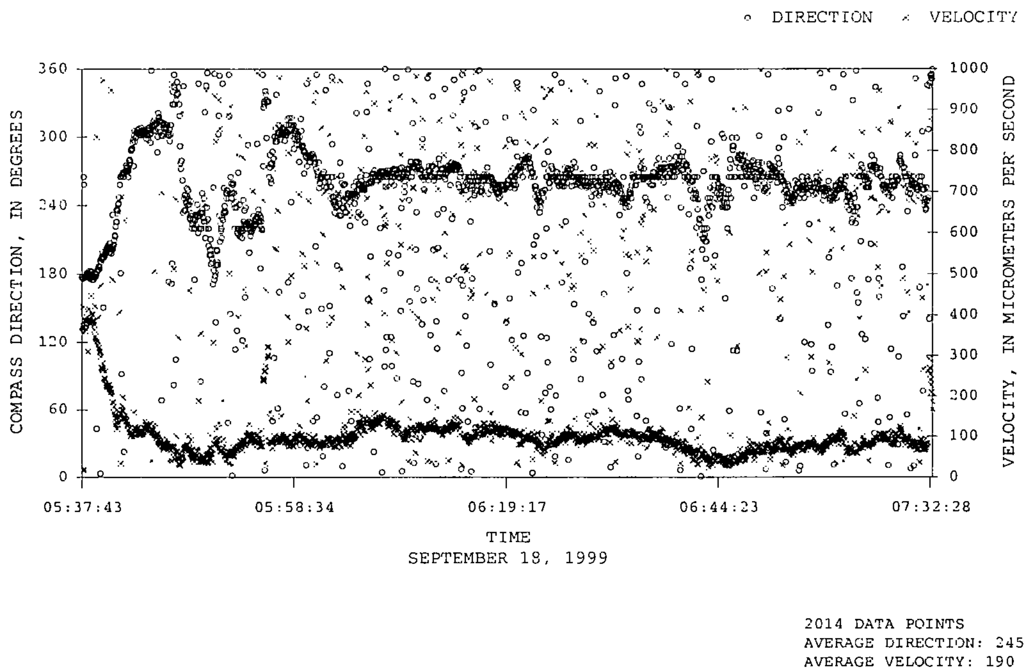


Figure 26. Colloidal borescope measurement at 178.00 feet in well JPG-5, Jefferson Proving Ground, Indiana.

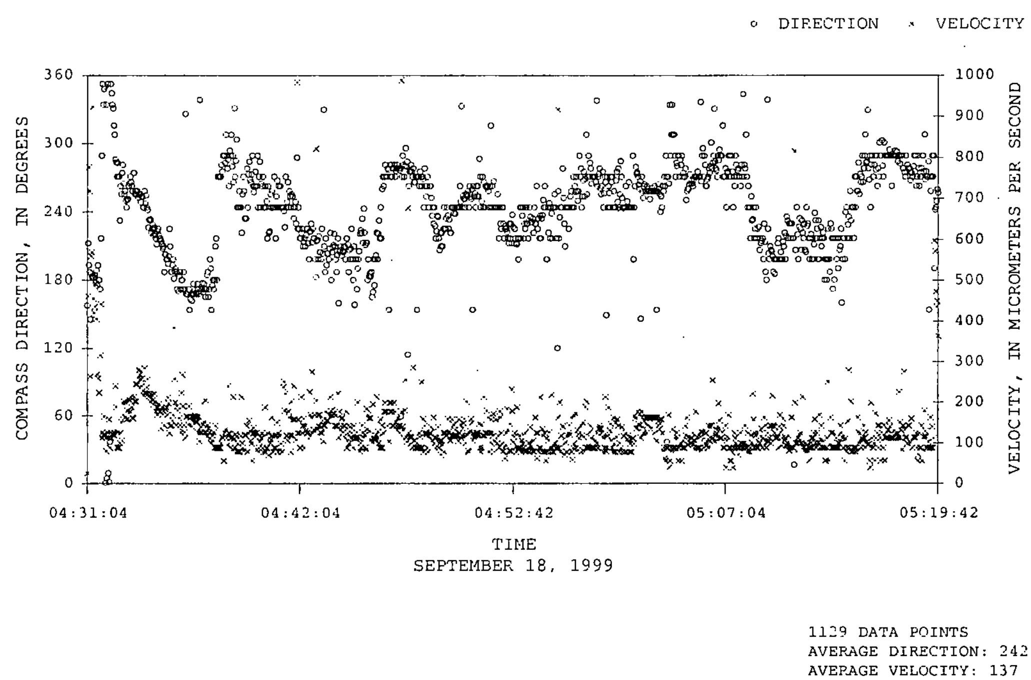


Figure 27. Colloidal borescope measurement at 195.00 feet in well JPG-5, Jefferson Proving Ground, Indiana.

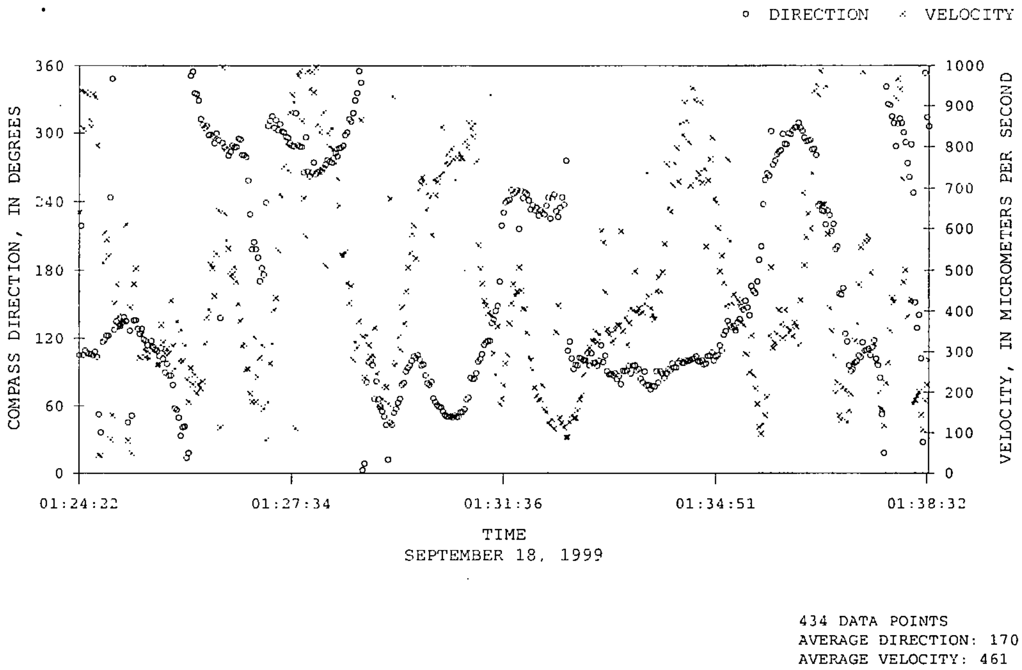


Figure 28. Colloidal borescope measurement that shows swirling, nondirectional flow and highly variable velocities.

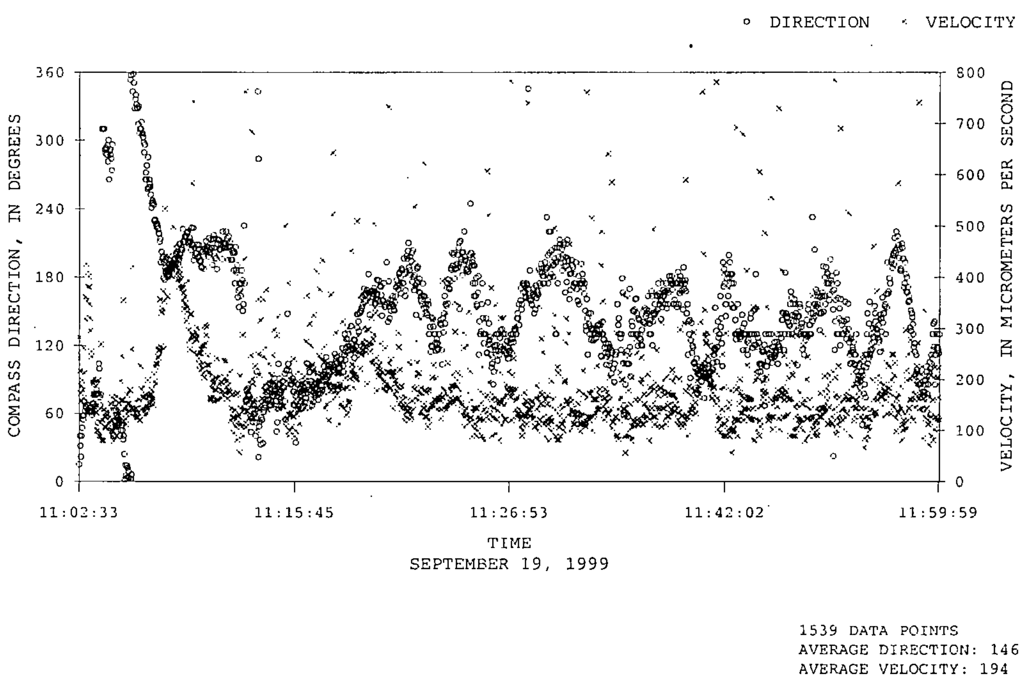


Figure 29. Colloidal borescope measurement at 46.53 feet in well JPG-2, Jefferson Proving Ground, Indiana.

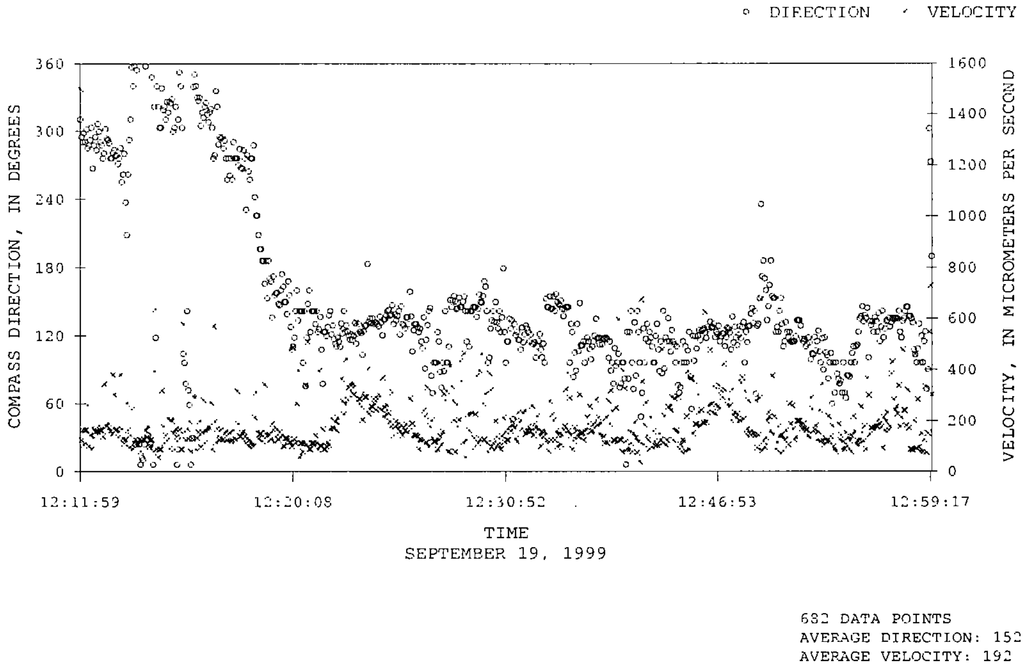


Figure 30. Colloidal borescope measurement at 48.66 feet in well JPG-2, Jefferson Proving Ground, Indiana.

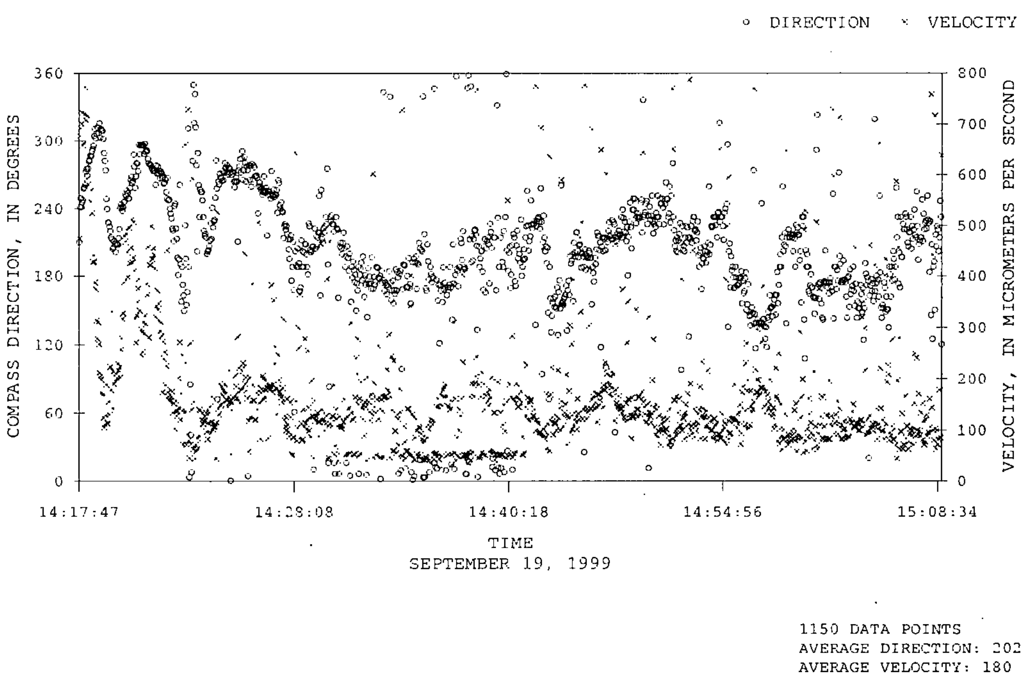


Figure 31. Colloidal borescope measurement at 58.38 feet in well JPG-2, Jefferson Proving Ground, Indiana.

Table 17. Borehole measurements of ground-water flow made with the colloidal borescope in well JPG-2, Jefferson Proving Ground, Indiana, September 19, 1999

[Depth is measured from top of casing; ft, foot; Flow direction is compass direction relative to true north; μm/s, micrometers per second; ft/d, foot per day]

Depth (ft)	Flow direction (degrees)	Velocity in borehole (μm/s)	Velocity in borehole (ft/d)
41.75	137	169	47
42.17	126	172	48
44.01	136	178	50
46.53[a]	146	194	54
48.66[a]	152	192	54
50.34	155	230	64
53.48	160	407	114
54.02	156	376	105
55.51	211	241	68
57.38	206	240	67
58.38[a]	202	180	50
60.76	179	247	69
178.00	166	177	50
180.00	253	220	62
182.00	199	178	50
183.50	203	386	108
185.00	241	340	95
187.50	242	348	97
190.00	207	234	66
195.00	252	357	100

[a]Measurement at this depth was determined to have consistent flow.

After the measurements were completed under ambient conditions in well JPG-2, nearby well JPG-1 was pumped the next day at an average rate of 0.76 gal/min to induce horizontal ground-water flow to the pumped well. The flow measurements made in well JPG-2 while pumping well JPG-1 are listed in table 18. The time of measurement in table 18 corresponds to the midpoint of data collection and is plotted on the drawdown curve for well JPG-2 (fig. 32). Depths that showed consistent flow under ambient conditions were tested during the early part of the pumping. The measurement at 46.53 ft showed the effect of the pumping that started at 09:22 (fig. 33). Prior to the pumping, the average flow direction was to the south but, once

Table 18. Borehole measurements of ground-water flow made with the colloidal borescope in well JPG-2 while pumping nearby well JPG-1, Jefferson Proving Ground, Indiana, September 20, 1999

[Depth is measured from top of casing; ft, foot; Flow direction is compass direction relative to true north; μm/s, micrometers per second; ft/d, foot per day]

Depth (ft)	Time	Flow direction (degrees)	Velocity in borehole (μm/s)	Velocity in borehole (ft/d)
42.00	13:58	182	135	38
44.01	12:11	180	106	30
45.00	14:21	168	162	45
46.53	09:37	315	134	38
47.50	15:41	156	123	34
48.00[a]	16:02	254	130	36
48.66[a]	11:33	134	123	34
50.34[a]	10:44	277	85	24
53.48	12:33	176	109	30
54.02	12:58	173	120	34
58.38	13:36	188	99	28
182.00[a]	16:40	263	226	63
184.00	17:38	187	214	60

[a]Measurement at this depth was determined to have consistent flow.

the pump was turned on, the flow direction showed considerable variability. A consistent flow direction was never achieved during the measurement at 46.53 ft.

Measurements that showed fairly consistent flow during the pumping were made at depths of 48.00, 48.66, 50.34, and 182.00 ft (figs. 34–37). The zone at 48.00 ft was not measured under ambient conditions; during the pumping, it yielded an average velocity of 36 ft/d and an average flow direction of 254 degrees. The measurements at 48.00, 50.34, and 182.00 ft recorded flow directions to the west, more towards the pumping well, than during the ambient measurements. The measurements made during pumping yielded lower average velocities than those during ambient conditions.

Eight depths where measurements were made under ambient and pumping conditions are listed in table 19 (p. 73); all but one of the velocities are lower during the pumping than during ambient conditions. At a depth of 182.00 ft, the average

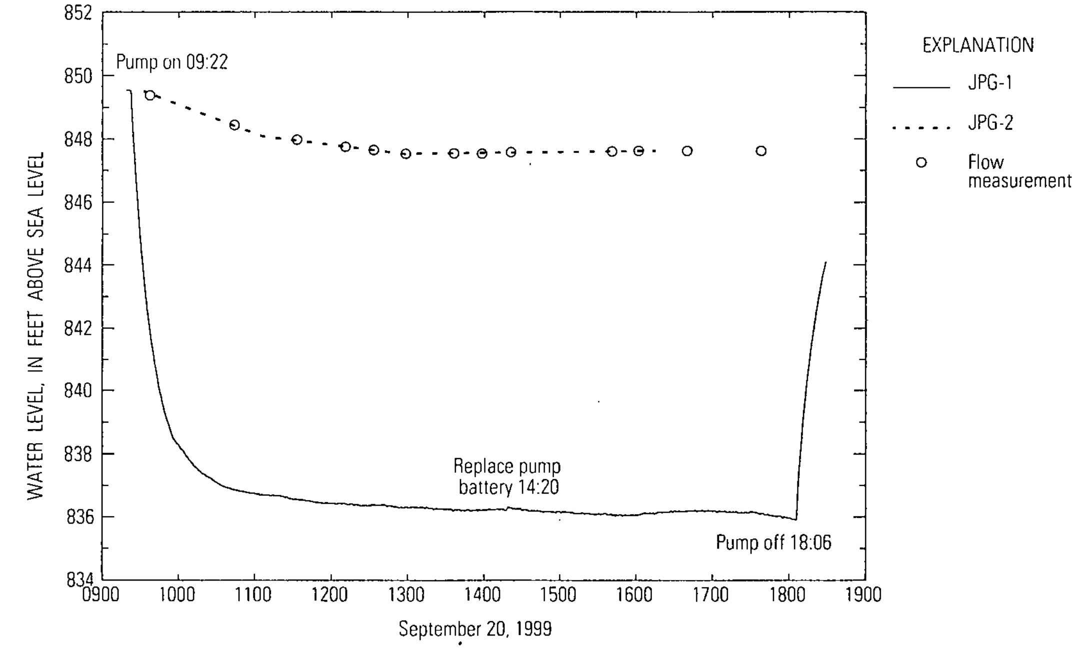


Figure 32. Drawdown curves for well JPG-2 and nearby well JPG-1, which was pumped at 0.76 gallon per minute, while measurements were made with the colloidal borescope in well JPG-2, Jefferson Proving Ground, Indiana.

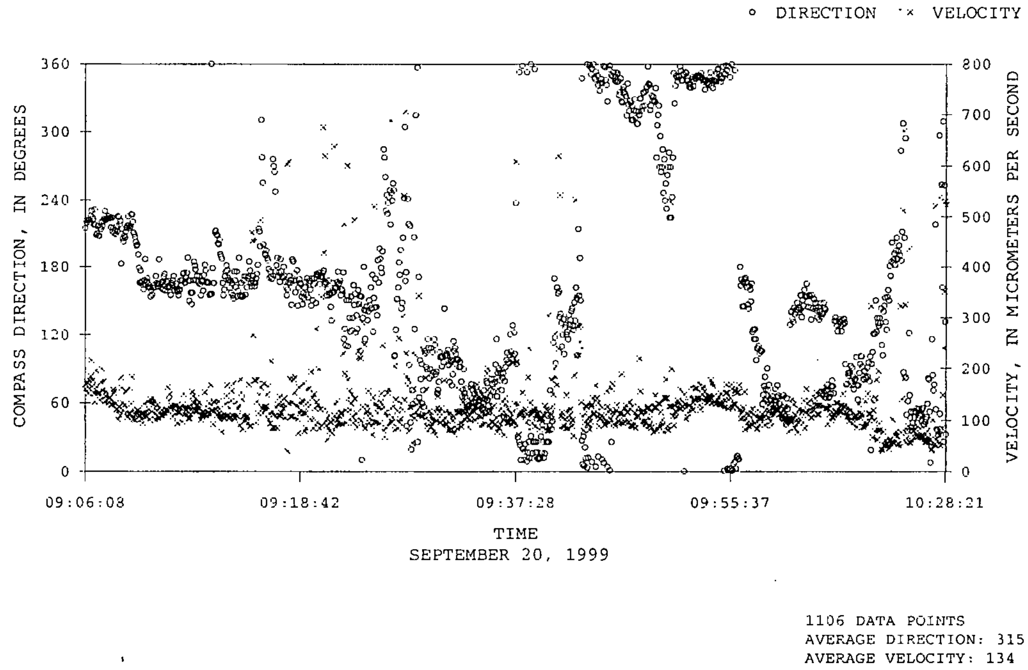


Figure 33. Colloidal borescope measurement at 46.53 feet in well JPG-2, showing the effects of the pumping that started at 09:22 in nearby well JPG-1, Jefferson Proving Ground, Indiana.

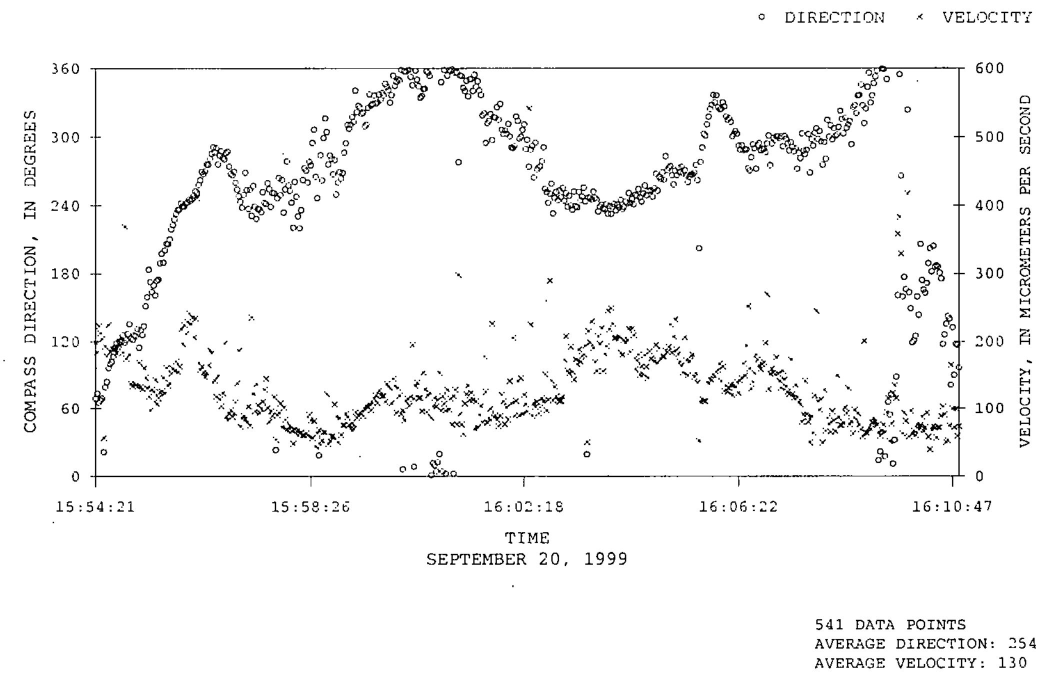


Figure 34. Colloidal borescope measurement at 48.00 feet in well JPG-2 while pumping nearby well JPG-1, Jefferson Proving Ground, Indiana.

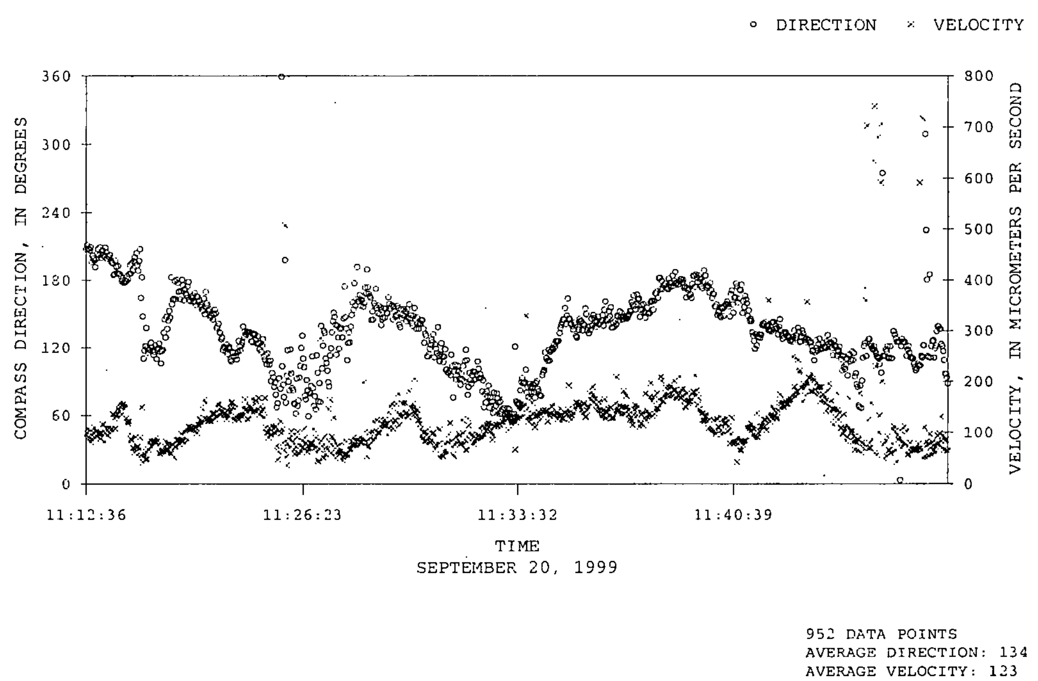


Figure 35. Colloidal borescope measurement at 48.66 feet in well JPG-2 while pumping nearby well JPG-1, Jefferson Proving Ground, Indiana.

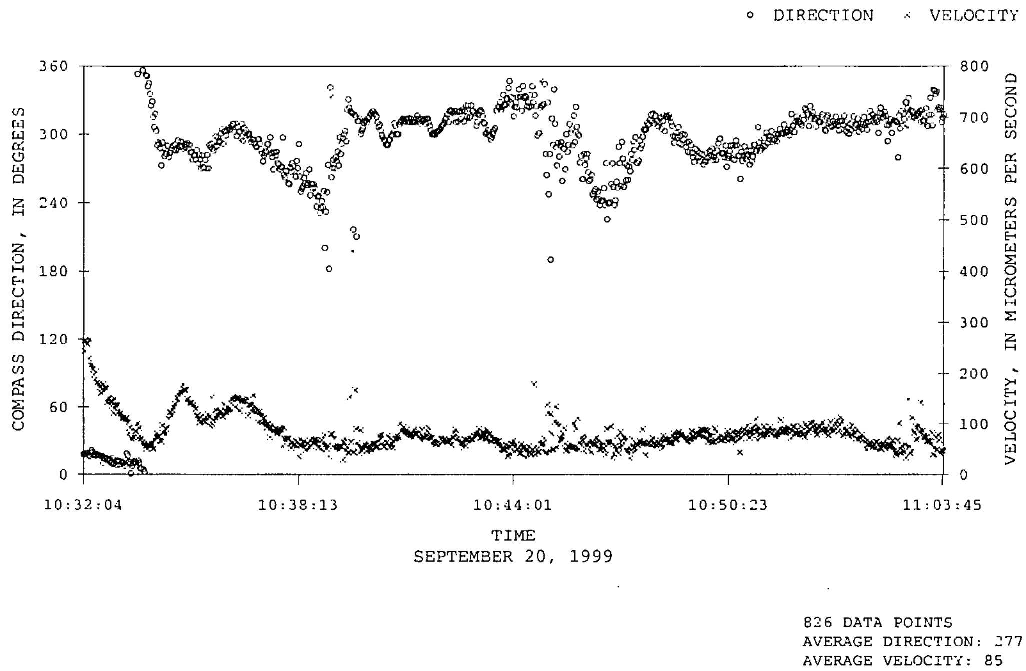


Figure 36. Colloidal borescope measurement at 50.34 feet in well JPG-2 while pumping nearby well JPG-1, Jefferson Proving Ground, Indiana.

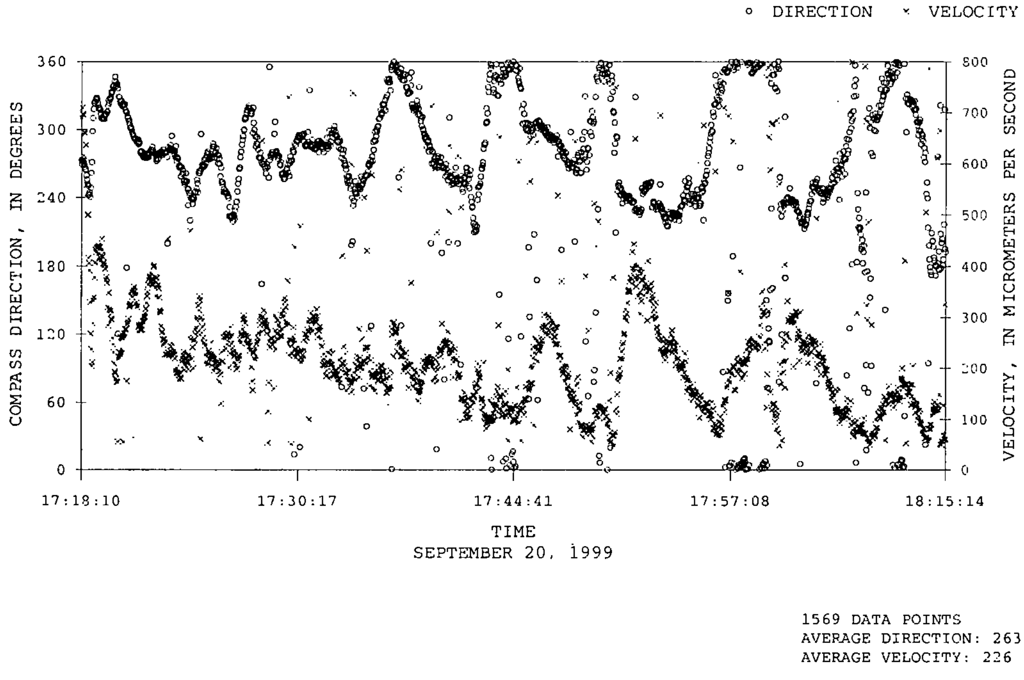


Figure 37. Colloidal borescope measurement at 182.00 feet in well JPG-2 while pumping nearby well JPG-1, Jefferson Proving Ground, Indiana.

Table 19. Borehole measurements of ground-water flow made with the colloidal borescope in well JPG-2 for ambient conditions and while pumping nearby well JPG-1, Jefferson Proving Ground, Indiana, September 19–20,1999

[Depth is measured from top of casing; ft, foot; Flow direction is compass direction relative to true north; ft/d, foot per day]

Depth (ft)	Flow direction while ambient (degrees)	Flow direction while pumping (degrees)	Velocity in borehole while ambient (ft/d)	Velocity in borehole while pumping (ft/d)	Elapsed pumping time (minutes)
44.01	136	180	50	30	169
46.53	146[a]	315	54[a]	38	15
48.66	152[a]	134[a]	54[a]	34[a]	131
50.34	155	277[a]	64	24[a]	82
53.48	160	176	114	30	191
54.02	156	173	105	34	216
58.38	202[a]	188	50[a]	28	254
182.00	199	263[a]	50	63[a]	438
Average	**163**	**213**	**68**	**35**	not averaged

[a]Measurement was determined to have consistent flow.

velocity during pumping was 63 ft/d compared to 50 ft/d during ambient conditions. The velocity data for this measurement, however, showed more variability than most of the other measurements in well JPG-2.

The drawdown curves for wells JPG-2 and JPG-1 indicate that, for most of the period of pumping, a water-level difference of 11 to 12 ft was maintained between the two wells (fig. 32). Also, as in the previous pumping tests, drawdown was observed in well JPG-2 shortly after the pumping began in well JPG-1, indicating that the wells had some hydraulic connection. The average flow direction during the pumping was 50 degrees west of the average flow direction for the ambient measurements (table 19). Most measurements, however, yielded highly variable flow directions without achieving a consistent flow direction. Because of the time variable, differences in the flow directions and velocities for ambient and pumping conditions were not computed; however, the data are presented to show the relative differences and the general trends.

The colloidal borescope measurements did not show the anticipated effect of increased velocities in well JPG-2. The overall trend of flow directions (table 19) was more towards the pumping well than during ambient conditions. The pumping time was probably insufficient to cause a consistent increase in velocity and to cause a complete change in flow direction towards the pumping well. The response in the low-permeability bedrock was delayed more than in a permeable sand aquifer or in a bedrock with open fractures. Even though well JPG-2 was in hydraulic connection with well JPG-1, it is possible that some of the tested zones were not.

The depths at which colloidal borescope measurements were made in well FC-29 are listed in table 20. The static water level during these measurements was 40.3 ft below the top of casing. Most of the measurements yielded swirling, nondirectional flow. Several measurements were made at depths adjacent to the two open fractures, including the middle of the fractures at depths of 67.20 and 91.42 ft. Measurements at depths of 67.80, 70.00, and 79.75 ft yielded relatively consistent flow velocities and directions. The measurement at 67.80 ft indicated a relatively high velocity zone at the upper fracture, with an average velocity of 230 ft/d and an average flow direction of 149 degrees (fig. 38). The June 1999 background logging indi-

Table 20. Borehole measurements of ground-water flow made with the colloidal borescope in well FC-29, Fort Campbell, Kentucky, September 22–23, 1999

[Depth is measured from top of casing; ft, foot; Flow direction is compass direction relative to true north; µm/s, micrometers per second; ft/d, foot per day; NR, no remark]

Depth (ft)	Flow direction (degrees)	Velocity in borehole (µm/s)	Velocity in borehole (ft/d)	Remarks
50.37	181	180	50	NR
53.92	156	153	43	NR
65.96	179	85	24	.2 ft above fracture
66.30	167	84	23	Fracture
67.20	114	279	78	Middle of fracture
67.80[a]	149	822	230	Fracture
67.80[a]	153	1,825	511	Repeat
70.00[a]	302	481	135	NR
79.75[a]	285	388	109	NR
90.76	188	628	176	Edge of fracture
91.12	171	804	225	Fracture
91.42	106	1,079	302	Middle of fracture
91.72	186	1,274	357	Fracture
92.06	211	1,720	482	Edge of fracture

[a]Measurement at this depth was determined to have consistent flow.

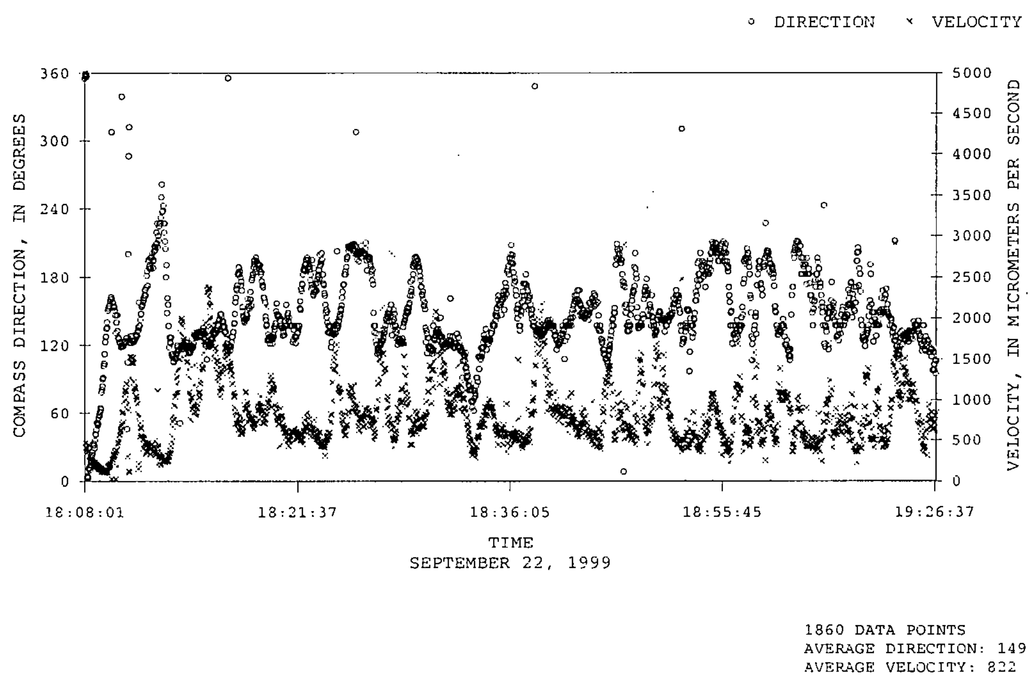


Figure 38. Colloidal borescope measurement at 67.80 feet in well FC-29, Fort Campbell, Kentucky.

cated that about 0.15 gal/min of flow enters the well at this fracture and moves vertically down to the lower fracture. The flow-direction data show variability, as most measurements do; to have the relative consistency as shown in figure 38, the measurement probably was not affected by the vertical flow below this fracture.

One repeat measurement was made to test the reliability of the magnetometer in the colloidal borescope. The repeat measurement, at a depth of 67.80 ft, was made the day after the original measurement at this depth. The second measurement yielded an average velocity in the borehole of 511 ft/d, more than twice the original measurement; however, the average flow direction of 153 degrees was almost identical to the original (fig. 39). The velocity data for the repeat measurement showed more variability than the original measurement, but the direction data showed less variability than the original measurement (figs. 38 and 40). The difference in velocities for the two measurements may be attributed to changes in the hydraulic conditions over the 18 hours between the two measurements.

The measurements at 70.00 and 79.75 ft were made in an area of the borehole where vertical flow occurs between the two open fractures. The measurement at 70.00 ft yielded an average velocity in the borehole of 135 ft/d and an average flow direction of 302 degrees (fig. 41). The measurement at 79.75 ft yielded an average velocity in the borehole of 109 ft/d and an average flow direction of 285 degrees (fig. 42). These two measurements do not appear to be affected by the vertical flow—the velocity and direction data are consistent, even though they show variability. It appears that the rubber disc attached to the colloidal borescope worked sufficiently to baffle the vertical flow.

Five measurements were made adjacent to the lower fracture, all of which indicated relatively high velocities. All of these measurements, however, had highly variable direction data, which did not allow for a reliable estimate of flow direction. Apparently, the downward vertical flow in the borehole causes a disturbance in the flow field or the flow exits the well in multiple directions. In either case, the flow conditions at the lower fracture restricted the capability of the colloidal borescope to measure a reliable flow direction.

The depths at which measurements were made in well FC-15 are listed in table 21 (p. 78). The static water level during these measurements was 91.3 ft below the top of casing. Measurements were made at the middle of each fracture at depths of 128.45, 143.52, and 154.78 ft, but none of these measurements yielded a reliable flow direction. The presence of vertical flow in the borehole could have affected the measurements if the rubber disc did not sufficiently baffle the vertical flow. Ambient vertical flow in the borehole between the open fractures was identified with the June 1999 background vertical-flow logging. The vertical-flow logging indicated that about 0.4 gal/min flowed from the upper fracture down to the second fracture, and about 0.08 gal/min flowed from the lower fracture up to the second fracture (fig. 12). Most of the measurements in well FC-15 yielded swirling, nondirectional flow.

Three measurements, at depths of 124.41, 128.00, and 145.50 ft, yielded relatively consistent flow directions and velocities. The measurements at 124.41 and 128.00 ft were above the first open fracture and should have been above the zone of vertical flow in the borehole. The measurement at 124.41 ft yielded an average velocity of 77 ft/d and an average flow direction of 234 degrees (fig. 43, p. 79). The measurement at 128.00 ft yielded an average velocity of 31 ft/d and an average flow direction of 261 degrees (fig. 44). The measurement at 145.50 ft was below the second fracture and yielded an average velocity of 118 ft/d and an average flow direction of 126 degrees (fig. 45, p. 80).

The measurement at the middle of the second fracture, at a depth of 143.52 ft, showed high velocities; however, inflow from the fracture and subsequent vertical flow caused enough disturbance to prevent a consistent flow direction. Hydrophysical logging (which will be discussed in the next section) was completed 2 days prior to the colloidal borescope measurements in well FC-15 and indicated that flow entered the well from the second fracture and moved vertically through the borehole to the upper and lower fractures.

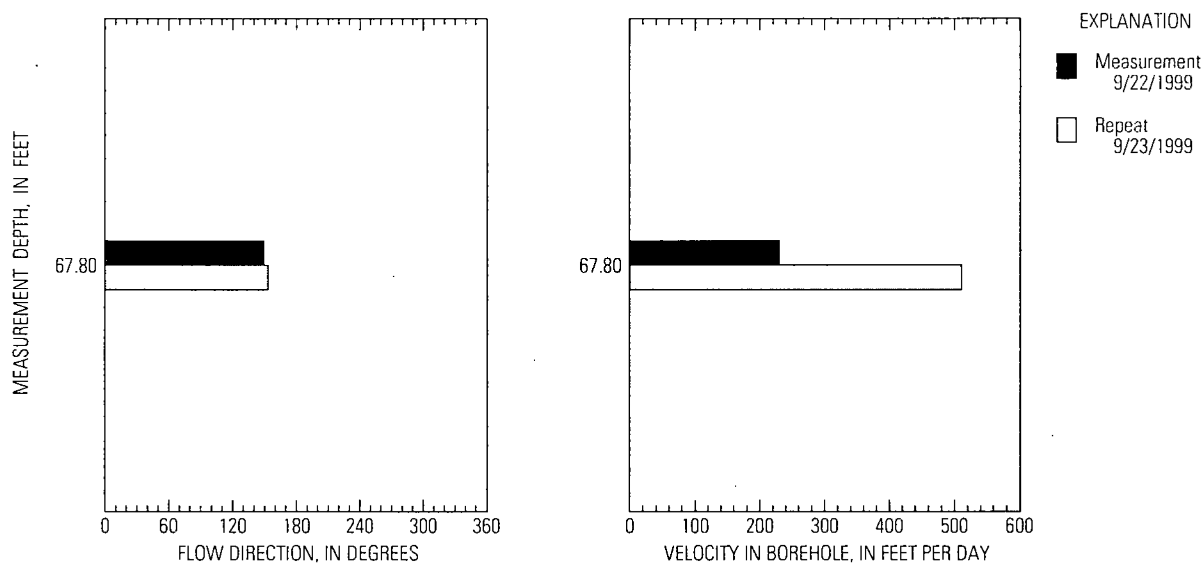


Figure 39. Flow directions and velocities for two measurements made with the colloidal borescope at a depth of 67.80 feet in well FC-29, Fort Campbell, Kentucky.

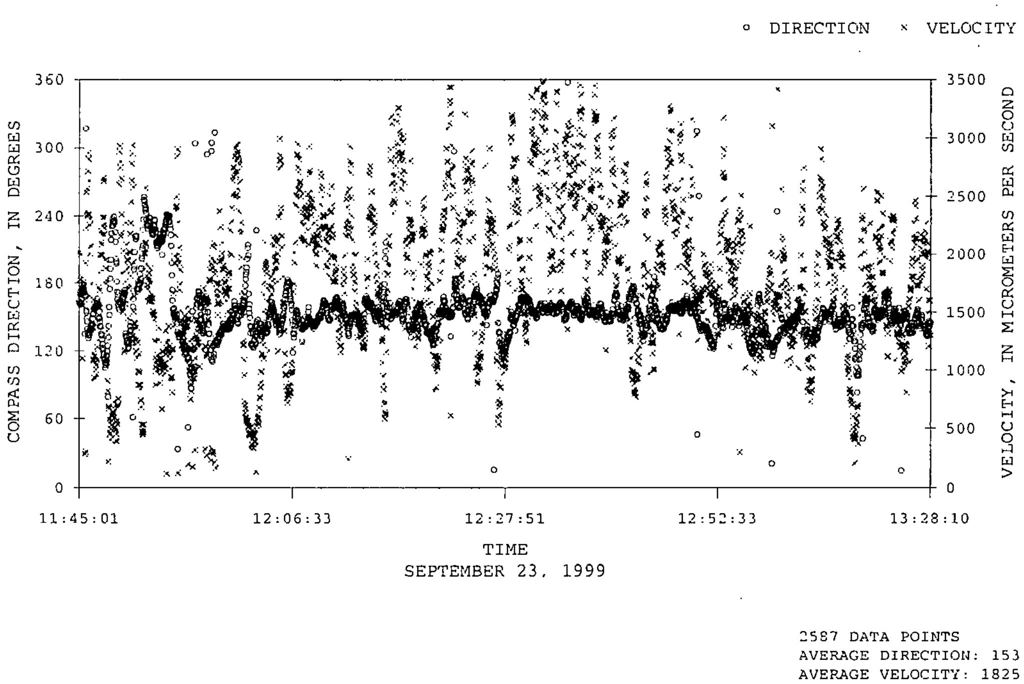


Figure 40. A repeat colloidal borescope measurement at 67.80 feet in well FC-29, Fort Campbell, Kentucky.

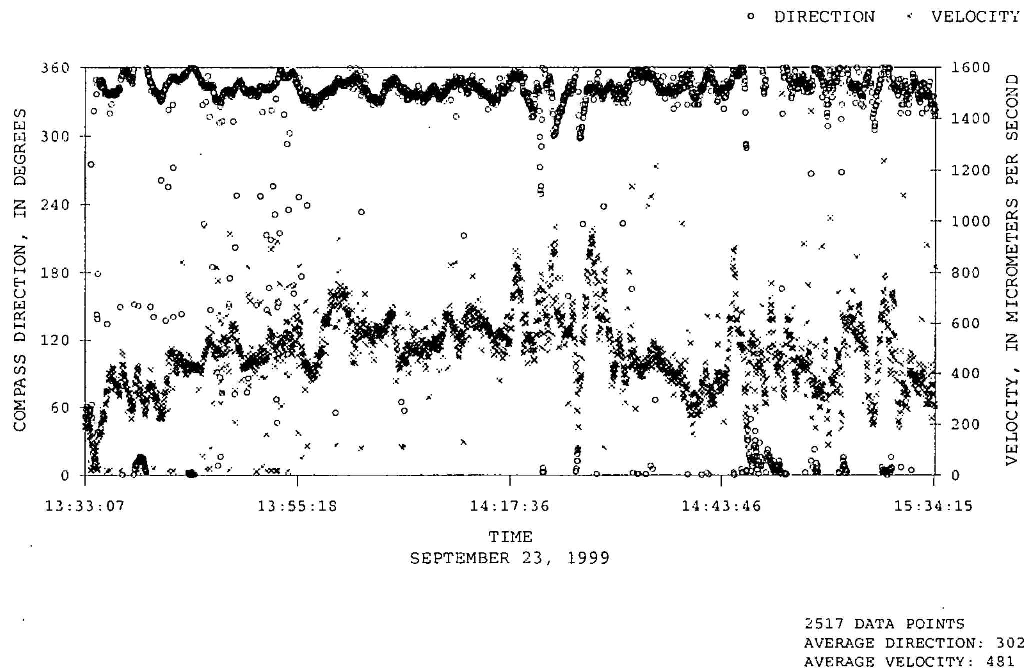


Figure 41. Colloidal borescope measurement at 70.00 feet in well FC-29, Fort Campbell, Kentucky.

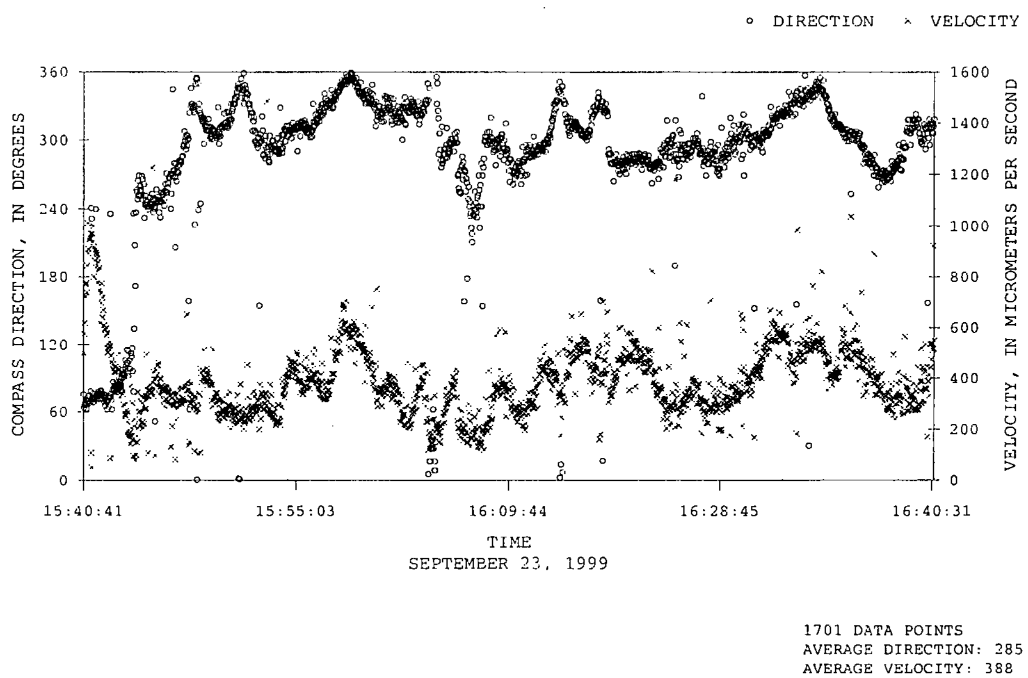


Figure 42. Colloidal borescope measurement at 79.75 feet in well FC-29, Fort Campbell, Kentucky.

Table 21. Borehole measurements of ground-water flow made with the colloidal borescope in well FC-15, Fort Campbell, Tennessee, September 24, 1999

[Depth is measured from top of casing; ft, foot; Flow direction is compass direction relative to true north; µm/s, micrometers per second; ft/d, foot per day; NR, no remark]

Depth (ft)	Flow direction (degrees)	Velocity in borehole (µm/s)	Velocity in borehole (ft/d)	Remarks
84.90	166	162	45	NR
104.90	186	337	94	NR
114.63	182	370	103	NR
116.27	190	391	109	NR
124.41[a]	234	275	77	NR
128.00[a]	261	110	31	.2 ft above fracture
128.45	161	80	22	Middle of fracture
128.90	158	156	44	.2 ft below fracture
130.10	227	204	57	NR
143.52	143	2,711	759	Middle of fracture
145.50[a]	126	420	118	NR
150.77	171	800	224	NR
154.25	191	549	154	.3 ft above fracture
154.55	222	1,491	417	Edge of fracture
154.78	194	1,036	290	Middle of fracture
155.00	177	135	38	Edge of fracture
155.30	191	125	35	.3 ft below fracture
156.80	213	177	50	NR

[a]Measurement at this depth was determined to have consistent flow.

The results of the hydrophysical logging indicate that the ambient vertical-flow regime in well FC-15 had changed since the June vertical-flow logging. At the time of the colloidal-borescope measurements and hydrophysical logging, the static water level was 6 ft lower than during the background logging.

Two measurements at the third fracture, at depths of 154.55 and 154.78, also showed high velocities without a consistent flow direction. Vertical flow exiting the borehole at this fracture probably caused enough disturbance to the flow field to prevent the measurement of a consistent flow direction. The vertical flow would have been superimposed on any natural horizontal flow moving through this fracture across the borehole.

The measurements made in well FC-16 are listed in table 22. The static water level during these measurements was 55.7 ft below the top of casing. Most of the measurements indicated swirling, nondirectional flow. Three measurements were made at the middle of the open fracture at 80.91 ft; however, only one measurement yielded a consistent flow direction. The third measurement at 80.91 ft yielded an average velocity of 29 ft/d and an average flow direction of 99 degrees (fig. 46, p. 81).

Measurements at 97.30 and 98.00 ft yielded fairly consistent velocities with higher variability

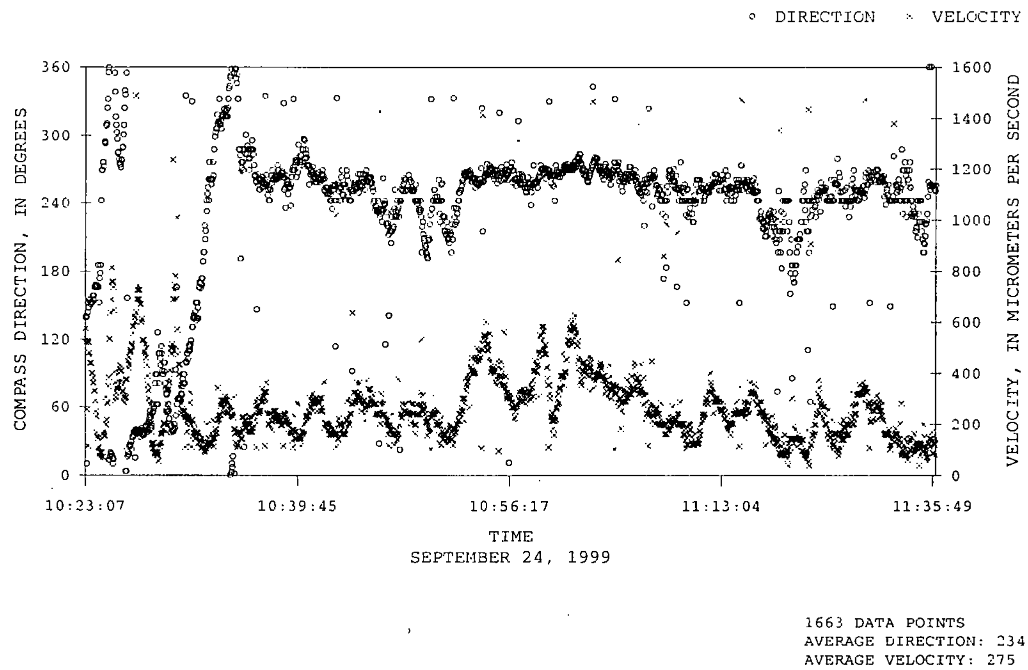


Figure 43. Colloidal borescope measurement at 124.41 feet in well FC-15, Fort Campbell, Tennessee.

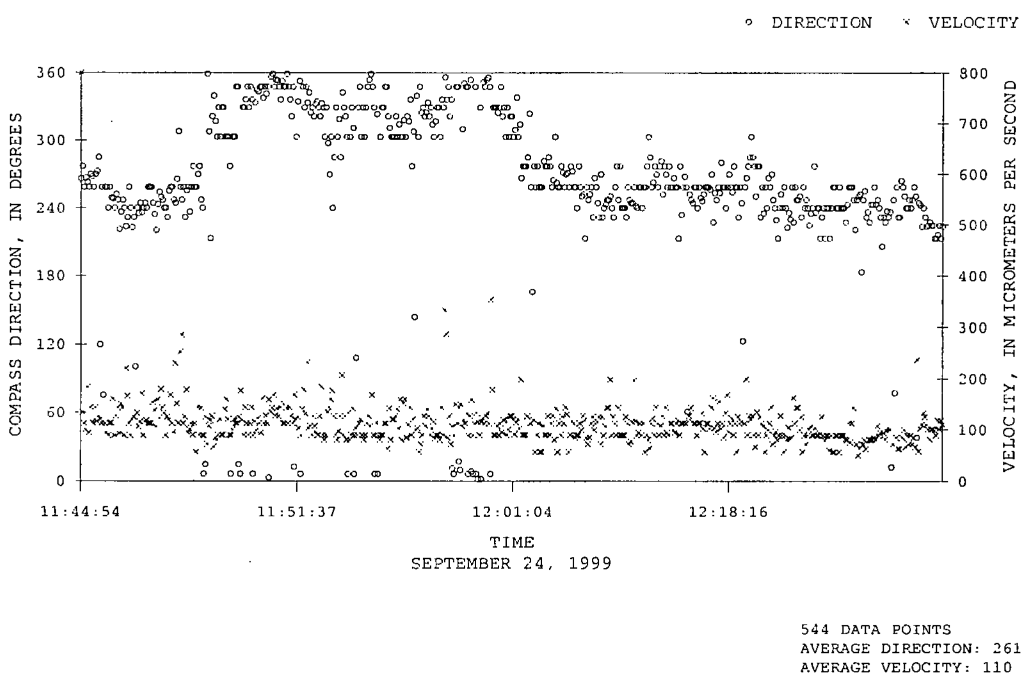


Figure 44. Colloidal borescope measurement at 128.00 feet in well FC-15, Fort Campbell, Tennessee.

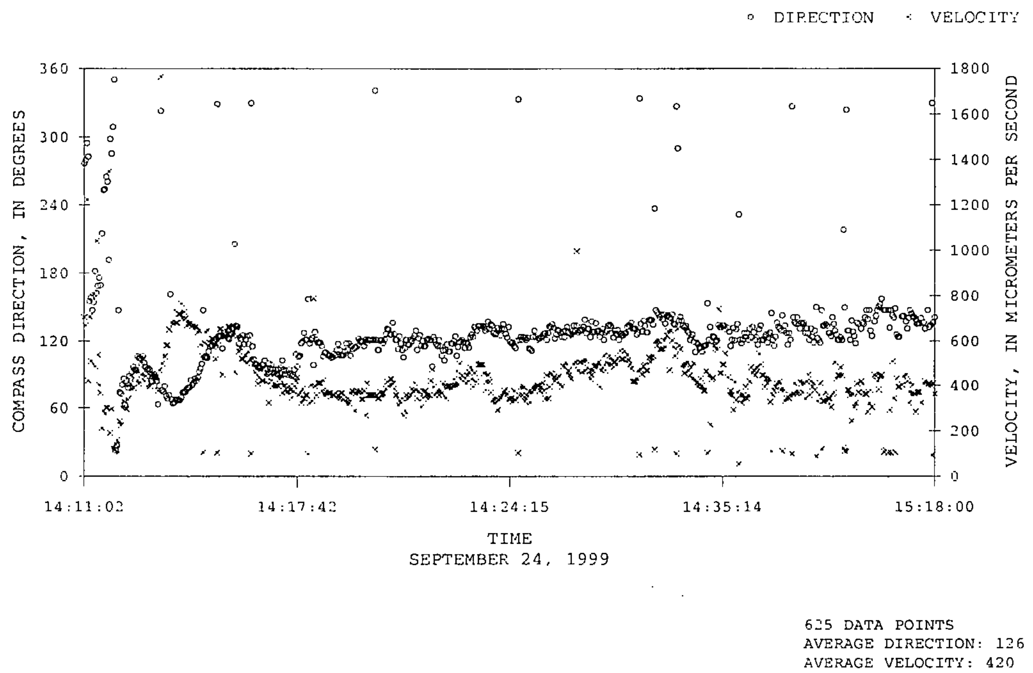


Figure 45. Colloidal borescope measurement at 145.50 feet in well FC-15, Fort Campbell, Tennessee.

Table 22. Borehole measurements of ground-water flow made with the colloidal borescope in well FC-16, Fort Campbell, Kentucky, September 21–22, 1999

[Depth is measured from top of casing; ft, foot; flow direction is compass direction relative to true north; µm/s, micrometers per second; ft/d, foot per day; NR, no remark]

Depth (ft)	Flow direction (degrees)	Velocity in borehole (µm/s)	Velocity in borehole (ft/d)	Remarks
78.50	146	117	33	NR
78.50	224	225	63	Repeat
80.46	145	128	36	.3 ft above fracture
80.46	180	226	63	Repeat
80.75	255	231	65	Edge of fracture
80.91	255	139	39	Middle of fracture
80.91	198	314	88	Repeat
80.91[a]	99	105	29	Repeat
81.36	209	108	30	.3 ft below fracture
82.00	206	189	53	NR
83.50	94	61	17	NR
84.00	157	50	14	NR
97.30[a]	216	189	53	NR
98.00[a]	211	216	60	NR
104.83	186	158	44	NR
130.90	133	130	36	NR
147.65	163	133	37	NR

[a]Measurement at this depth was determined to have consistent flow.

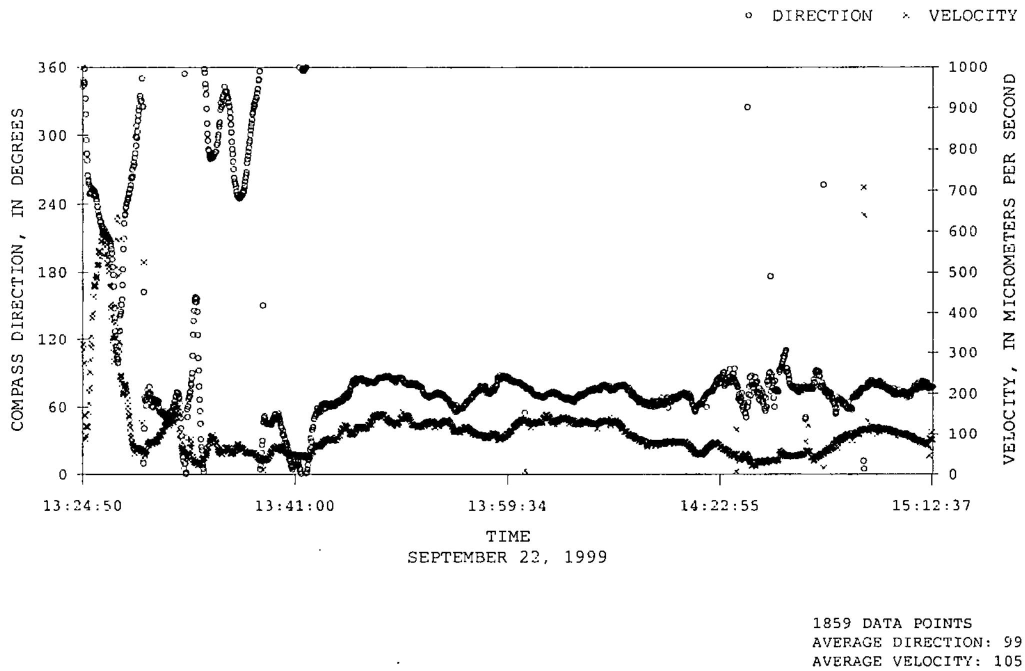


Figure 46. Colloidal borescope measurement at 80.91 feet in well FC-16, Fort Campbell, Kentucky.

in the flow directions. The measurements at 97.30 and 98.00 ft, however, had usable flow directions that could provide a general direction. The measurement at 97.30 ft had an average velocity of 53 ft/d and an average direction of 216 degrees (fig. 47, p. 82). The measurement at 98.00 ft had an average velocity of 60 ft/d and an average flow direction of 211 degrees (fig. 48). The variability in the velocity and direction—so common in the first few minutes of data collection—is illustrated in figure 46.

The flow directions and velocities for the multiple measurements made at depths of 78.50, 80.46, and 80.91 ft are shown in figure 49 (p. 83). None of the measurements at 78.50 and 80.46 ft were considered to have reliable flow directions and, as mentioned previously, only the third measurement at 80.91 ft yielded a reliable flow direction. As with the repeat measurement for well FC-29, some of the variability may be attributed to measurements made on different days.

Hydrophysical Logging

Hydrophysical logging was completed from September 15 through September 24, 1999, requiring about 1 day for each test at a well. The wells at JPG were logged September 15–18. Well JPG-5 was logged under ambient conditions; well JPG-2 was logged under ambient conditions and while pumping nearby well JPG-1 (fig. 6). The wells at Fort Campbell were logged September 20–24. Wells FC-29, FC-15, and FC-16 (fig. 7) were logged under ambient conditions. Wells FC-29 and FC-15 also were logged with a wireline packer set in the well to cut off the vertical flow and to isolate the horizontal flow in the upper fracture. Hydrophysical logging provided estimates of the ground-water velocity in the borehole over a range of depth rather than at a discrete point, as with the other flowmeter methods. Hydrophysical logging provided flow measurements estimated from measured changes in fluid-electrical conductivity along a length of borehole.

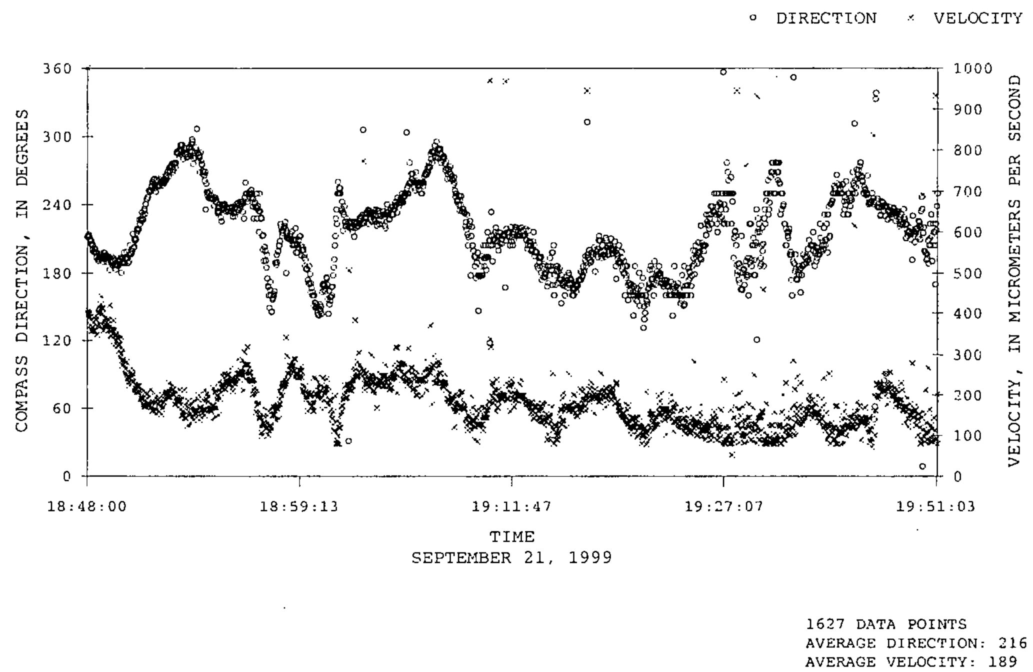


Figure 47. Colloidal borescope measurement at 97.30 feet in well FC-16, Fort Campbell, Kentucky.

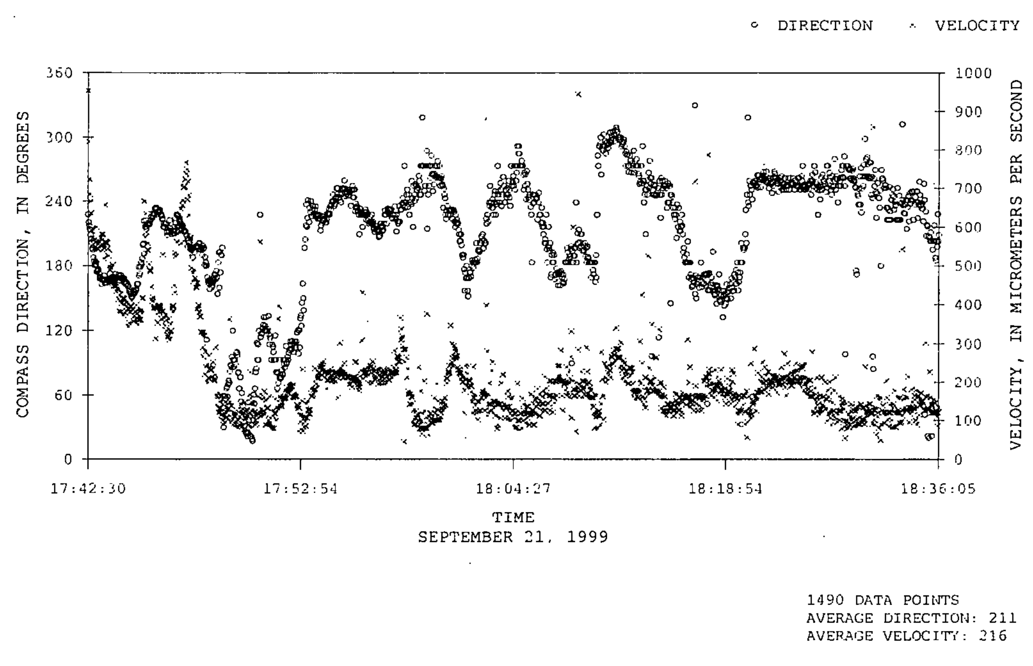


Figure 48. Colloidal borescope measurement at 98.00 feet in well FC-16, Fort Campbell, Kentucky.

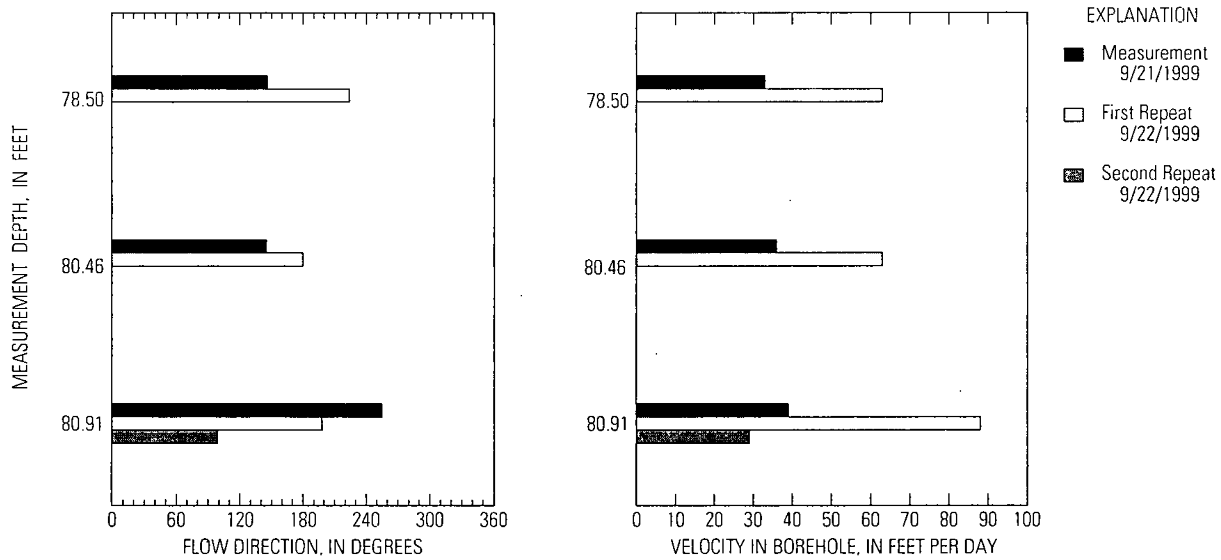


Figure 49. Flow directions and velocities for multiple measurements made with the colloidal borescope at selected depths in well FC-16, Fort Campbell, Kentucky.

The hydrophysical logging tool was calibrated for conductivity and temperature prior to data collection at each well. The logging tool then was lowered into the well and placed below the water surface to achieve thermal equilibrium. After the logging tool had reached thermal equilibrium, the background (pre-emplacement) fluid-electrical conductivity (FEC) and temperature were logged in the uncased part of the well. After the background log was completed, the fluid-management lines were moved into position. The injection line was lowered to within about 1 ft of the bottom of the well, and the submersible pump was positioned below the water surface. Deionized water was injected at the bottom of the well while the submersible pump extracted well water from near the water surface. The water level was monitored so that the pumping and injection rates were balanced to maintain a relatively stable head. The fluid-management system included control valves for throttling flow rates and flow totalizers for recording the volumes of extracted and injected water. A positive difference between the injected volume and the extracted volume is the amount of deionized water forced into the formation.

The logging tool was used to monitor the advance of the deionized water up the borehole as it displaced the fluid column in the well. The conductivity of the extracted water was monitored to determine if deionized water or diluted formation water had reached the top of the well. The emplacement procedure was complete when the logging tool, positioned near the submersible pump, and the extracted water showed that deionized water or sufficiently diluted formation water had reached the top of the well. When the fluid emplacement was complete, the well repeatedly was logged for FEC to monitor the time required to replace the deionized water in the borehole with formation water. The FEC and time data were used to calculate the mass-flux and borehole-dilution analyses for the depth zones where flow was indicated.

To apply the borehole-dilution technique to the appropriate logs, the FEC data acquired in each zone of interest were isolated. The data for a particular zone were plotted against time on semi-log graphs. The slope of the plotted lines was used to calculate ground-water velocity through each zone, using equation 8. These calculations and the graphs of FEC and time are included on the figures that show the results of the mass-flux and dilution analyses for each well.

In most of the logs, the FEC data do not fit a linear trend at the beginning of the analyses because deionized water was forced into the formation during the fluid exchange and/or the pressure had not stabilized. In either case, the water flowing into the well at early times was diluted formation water; therefore, the early-time data were not considered in the slope calculations. The results of the hydrophysical logging—the computed velocity in the borehole—are shown in table 23. All depths are referenced to the top of casing.

The background FEC log for well JPG-5 was done on September 15, and the fluid emplacement followed by a time series of logs was completed on September 16. The static water level in well JPG-5 was 12.3 ft below the top of casing. The background FEC log for well JPG-5 is shown in figure 50. The background log shows a large shift in the FEC, ranging from about 850 μS/cm (microsiemens per centimeter) near the top to about 9,000 μS/cm near the bottom. The high value of conductivity for the lower half of the well was not thought to be representative of the formation water, and it was not used for the analysis. Previous measurements of specific conductance for the background logging and ADV work were similar to the background value measured in the upper half

Table 23. Borehole measurements of ground-water flow made with the hydrophysical logging method in selected wells at Jefferson Proving Ground, Indiana, and Fort Campbell, Kentucky/Tennessee, September 15–24, 1999

[ft, foot; Depth is measured from top of casing; gal/min, gallon per minute; ft/d, foot per day; NR, no remark]

Well	Borehole diameter (ft)	Depth interval (ft)	Volumetric inflow rate[a] (gal/min)	Average volumetric velocity[b] (ft/d)	Velocity in borehole[c] (ft/d)	Remarks
JPG-5	0.42	40–44	0.002	0.23	0.12	NR
		160–200	.040	.46	.42	NR
JPG-2	.42	42–46	.010	1.15	.10	NR
		150–180	.006	.92	.12	NR
		180–196	.005	.14	.13	NR
JPG-2	.42	42–50	.003	.34	.34	Pumping well JPG-1
		150–180	.003	.05	.43	Pumping well JPG-1
		180–196	.003	.09	.36	Pumping well JPG-1
FC-29	.52	68–78	.021	.78	.77	Wireline packer used
FC-15	.52	102–119	.014	.30	.71	Wireline packer used
		130–137	.003	.16	.93	Wireline packer used

[a]Volumetric inflow rate is based on mass-flux analysis.

[b]Average volumetric velocity (v) is based on $Q = v \times A$, where Q is the volumetric inflow rate and A is the cross-sectional area of the borehole (diameter x length).

[c]Velocity in borehole is based on borehole-dilution analysis.

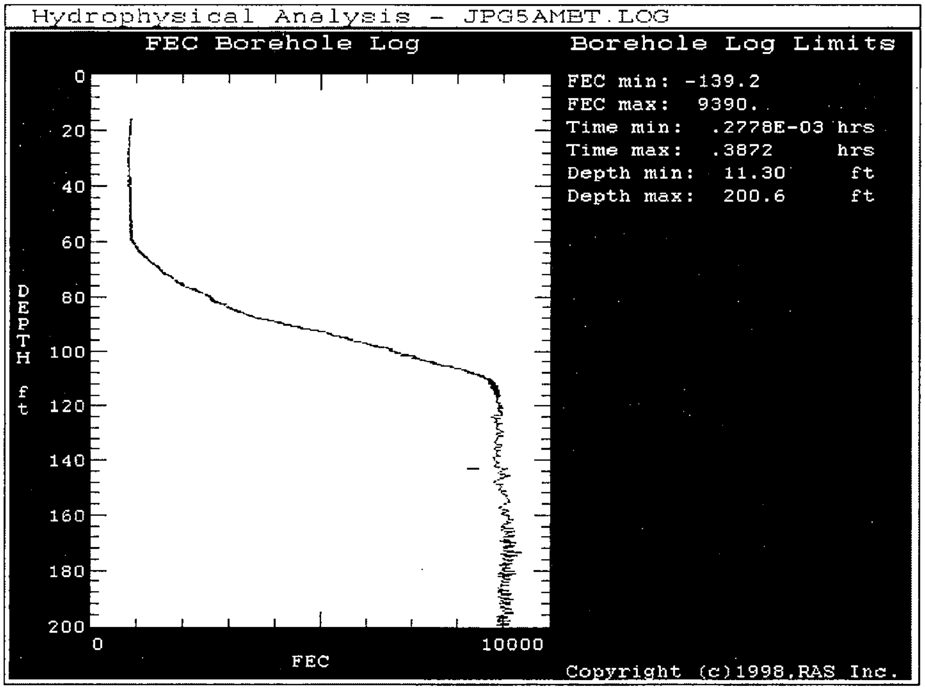


Figure 50. Background fluid-electrical-conductivity log for well JPG-5, Jefferson Proving Ground, Indiana.

of the well. The increase in formation-water FEC with depth in the JPG wells, however, is consistent with the formation-resistivity logs in figures 8 through 10. The figures show an appreciable decrease in formation resistivity below 100 ft that does not appear related to fracture permeability and may be attributed to electrically conductive saline water or brine saturating pore spaces in the formation.

During fluid emplacement, approximately 10 gal of deionized water were lost to the formation. Water level was monitored during and after the fluid emplacement. The water level returned to within 0.5 ft of the static water level within 30 minutes after the emplacement. A summary of the hydrophysical logs that were run after the fluid emplacement is given in figure 51. These logs suggested anomalies over the intervals 30 to 70 ft and 160 to 200 ft. The data for the interval 160 to 200 ft suggested horizontal flow was occurring; however, the data for the interval 30 to 70 ft suggested either possible inflow or a leak in the submersible pump during the logging. The possibility of a leaking pump required that a second fluid emplacement be done and the pump be removed following the emplacement.

A second fluid emplacement was completed, followed by another series of FEC logs. The second series of logs focused on the interval 30 to 100 ft (fig. 52). The logs indicated horizontal flow in the interval 40 to 44 ft. Mass-flux analysis (Loew and others, 1991) and traditional dilution analysis (Drost and others, 1968) were completed for the intervals 40 to 44 ft and 160 to 200 ft to calculate the volumetric inflow to the well and the velocity in the borehole. The FEC of the formation water for the mass-flux analysis was estimated as 850 μS/cm, based on field measurements during the background logging and ADV work and from the background FEC log. The mass-flux analysis for the upper interval 40 to 44 ft indicated a

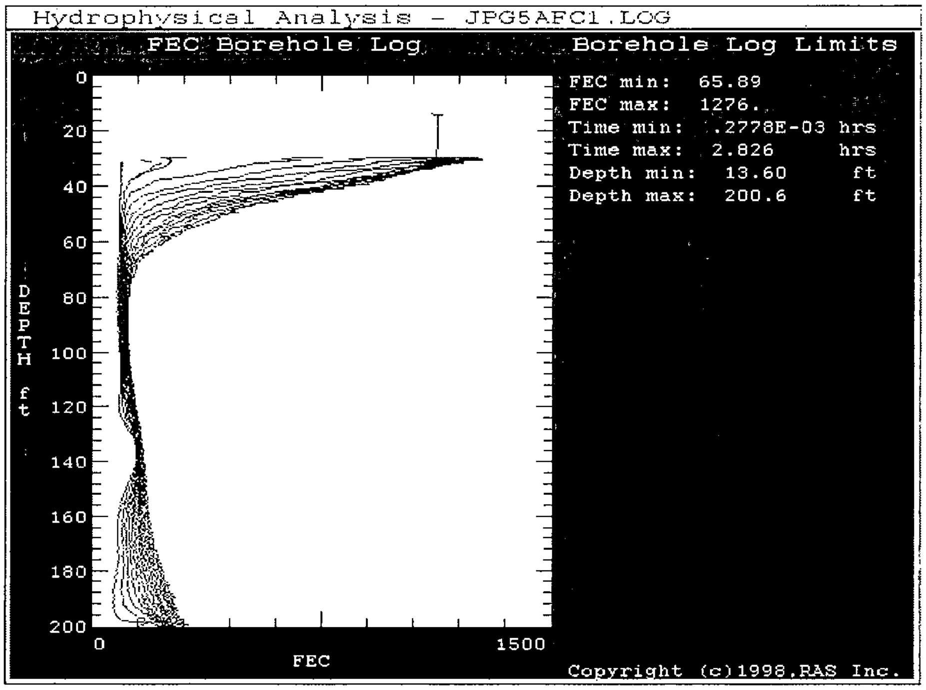


Figure 51. Hydrophysical log summary for well JPG-5, Jefferson Proving Ground, Indiana.

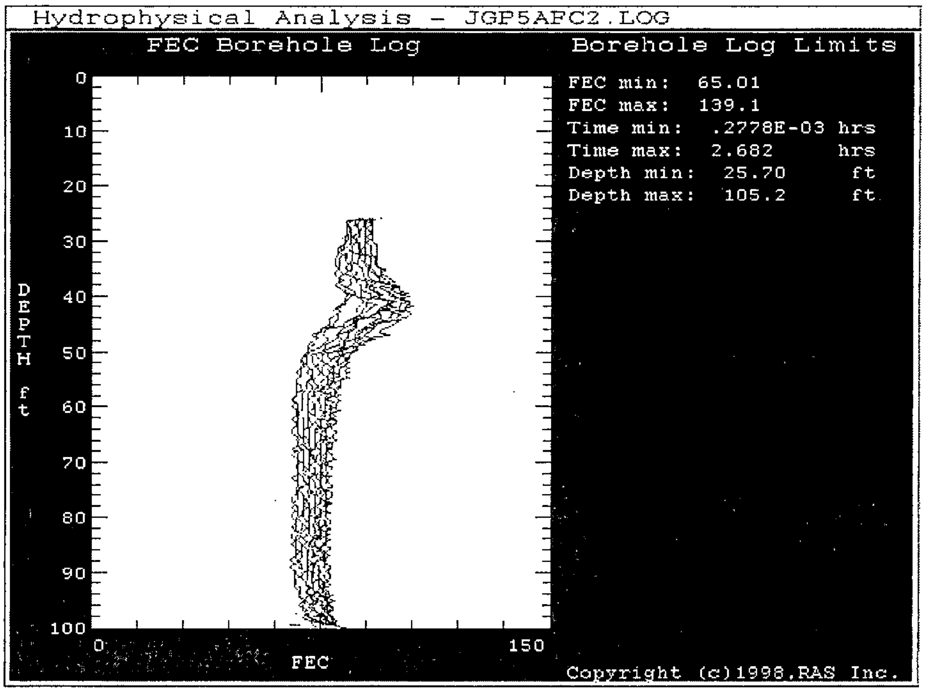


Figure 52. Hydrophysical log summary for the upper half of well JPG-5, Jefferson Proving Ground, Indiana.

volumetric inflow rate of 0.002 gal/min, and the dilution analysis indicated a velocity in the borehole of 0.12 ft/d (fig. 53, table 23). The volumetric inflow rate may be below the reasonable minimum for the integral-method algorithm used in the mass-flux analysis.

The mass-flux analysis for the lower test interval from 160 to 200 ft indicated a volumetric inflow rate of 0.04 gal/min, and the dilution analysis indicated a velocity of 0.42 ft/d (fig. 54, table 23). The interpretation of horizontal flow near the bottom of well JPG-5 is inconsistent with the June background vertical-flow logging, which identified no producing zones below 55 ft (table 1; fig. 10). The theory of vertical-flow-log interpretation shows that if two flow profiles (in this case, ambient and pumped) are developed, the analysis will detect any water-producing zones within two orders of magnitude lower than the zone transmissivity of the main producing zone (Paillet, 1998). The analysis for the interval 160 to 200 ft used an FEC of 850 µS/cm for the formation water, which is representative of the upper part of well JPG-5 but possibly not the lower part (fig. 50). The rate at which the hydrophysical logging shows FEC increasing in the borehole is given by the product of horizontal flow and formation-water FEC. If the FEC is assumed to be 10 times greater (as suggested in fig. 50), then the horizontal flow would be much less. The FEC in the deeper part of well JPG-5 may be underestimated in this analysis by more than a factor of 10, so the horizontal flow may be overestimated by more than a factor of 10. It was beyond the scope of this study to resolve the inconsistency between the vertical-flow logging and the hydrophysical logging in the deeper half of well JPG-5. Results of the hydrophysical logging are presented as they were computed by the contractor, RAS, Inc.

Hydrophysical logging was completed in well JPG-2 during ambient conditions on September 17 and while pumping nearby well JPG-1 on September 18. The static water level during the hydrophysical logging was 16.8 ft below the top of casing, and the bottom of casing was at 38.3 ft. The background FEC log for well JPG-2 is shown in figure 55 (p. 90). During fluid emplacement, approximately 10 gal of deionized water were lost to the formation. The water level was monitored during and after the fluid emplacement. The water level returned to within 0.5 ft of the static water level within 30 minutes after the emplacement. A summary of the hydrophysical logs that were run after the fluid emplacement is given in figure 56. These logs suggest anomalies over the intervals 42 to 46 ft, 150 to 180 ft, and 180 to 196 ft. The interval of greatest interest is the upper half of the well and is shown at a larger scale in figure 57 (p. 91).

Mass-flux analysis and dilution analysis were completed for the intervals 42 to 46 ft, 150 to 180 ft, and 180 to 196 ft to calculate the volumetric inflow to the well and the velocity in the borehole. The FEC of the formation water for the mass-flux analysis was estimated as 1,000 µS/cm and was based on field measurements during the background logging and ADV work and from the background FEC log (fig. 55). The mass-flux analysis for the upper interval 42 to 46 ft indicated a volumetric inflow rate of 0.01 gal/min, and the dilution analysis indicated a velocity in the borehole of 0.10 ft/d (fig. 58, table 23). The mass-flux analysis for the test interval 150 to 180 ft indicated a volumetric inflow rate of 0.006 gal/min, and the dilution analysis indicated a velocity in the borehole of 0.12 ft/d (fig. 59, p. 93). The mass-flux analysis for the lower interval 180 to 196 ft indicated a volumetric inflow rate of 0.005 gal/min, and the dilution analysis indicated a velocity in the borehole of 0.13 ft/d (fig. 60, p. 94). The volumetric inflow rates for these test intervals may be below the reasonable minimum for the integral-method algorithm used in the mass-flux analysis.

The interpretation of horizontal flow near the bottom of well JPG-2 is inconsistent with the June background vertical-flow logging that identified no producing zones below 65 ft (table 1, fig. 9). The analyses for the intervals 150 to 180 ft and 180 to 196 ft used an FEC of 1,000 µS/cm for the formation water, which is representative of the upper part of well JPG-2 but possibly not of the lower part (fig. 55). As was mentioned for

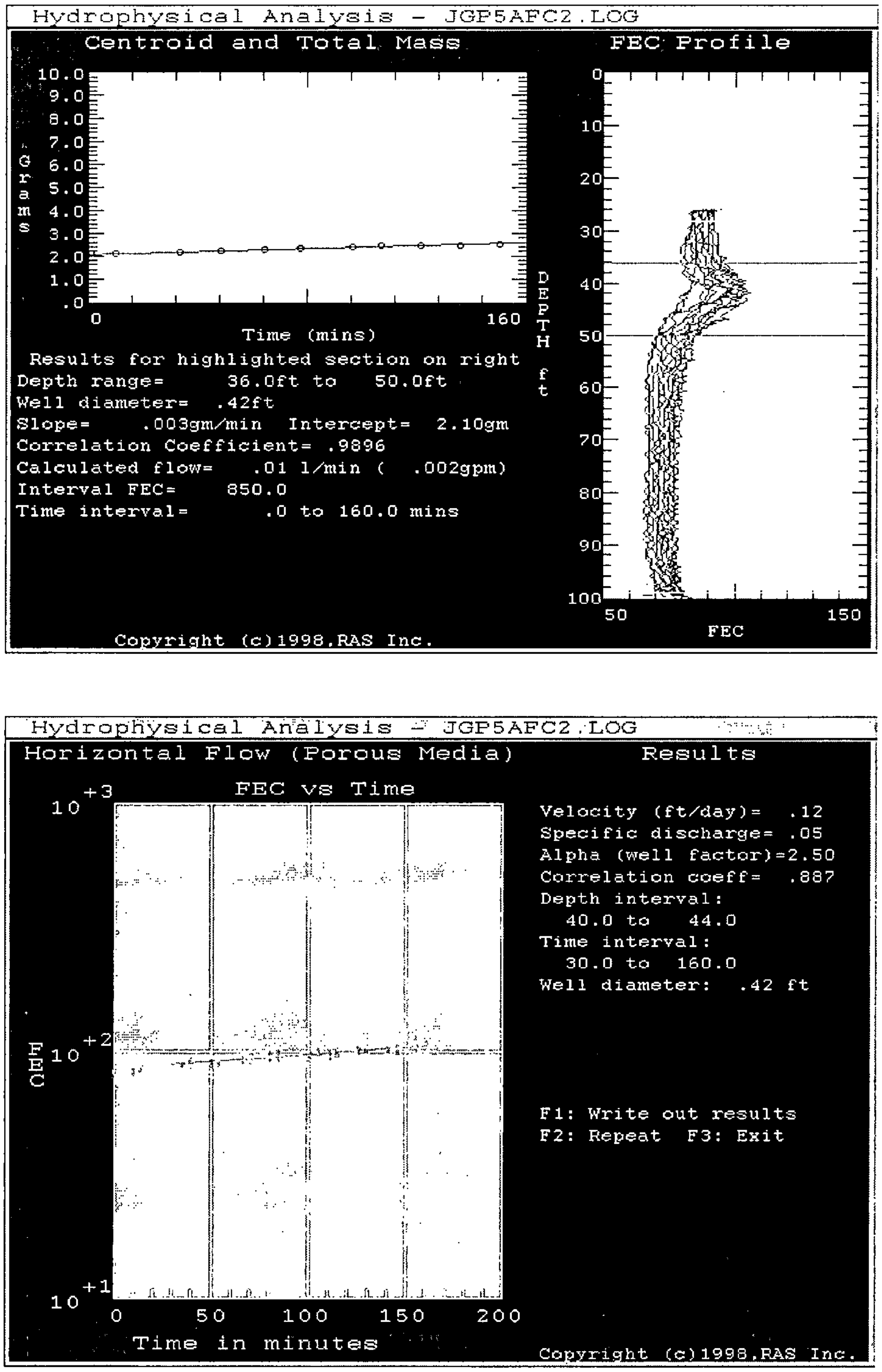
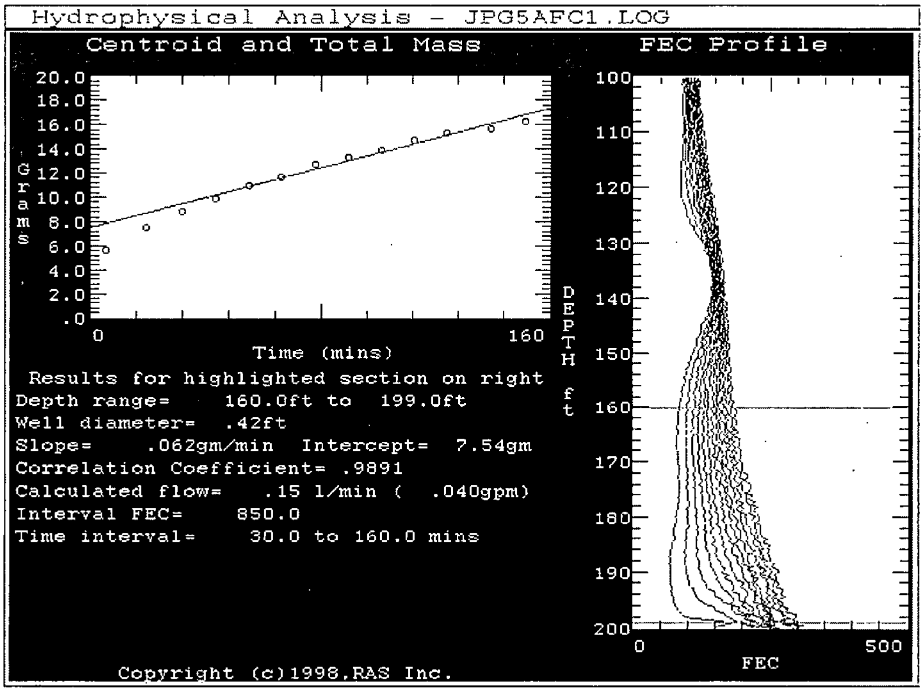


Figure 53. Results of mass-flux analysis and dilution analysis for the test interval 40 to 44 feet in well JPG-5, Jefferson Proving Ground, Indiana.



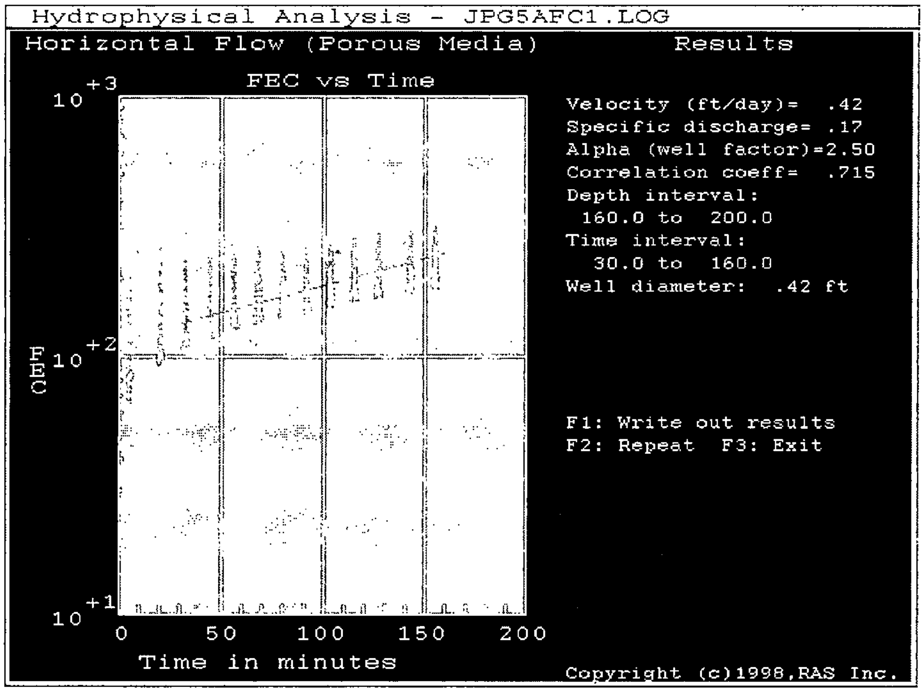


Figure 54. Results of mass-flux analysis and dilution analysis for the test interval 160 to 200 feet in well JPG-5, Jefferson Proving Ground, Indiana.

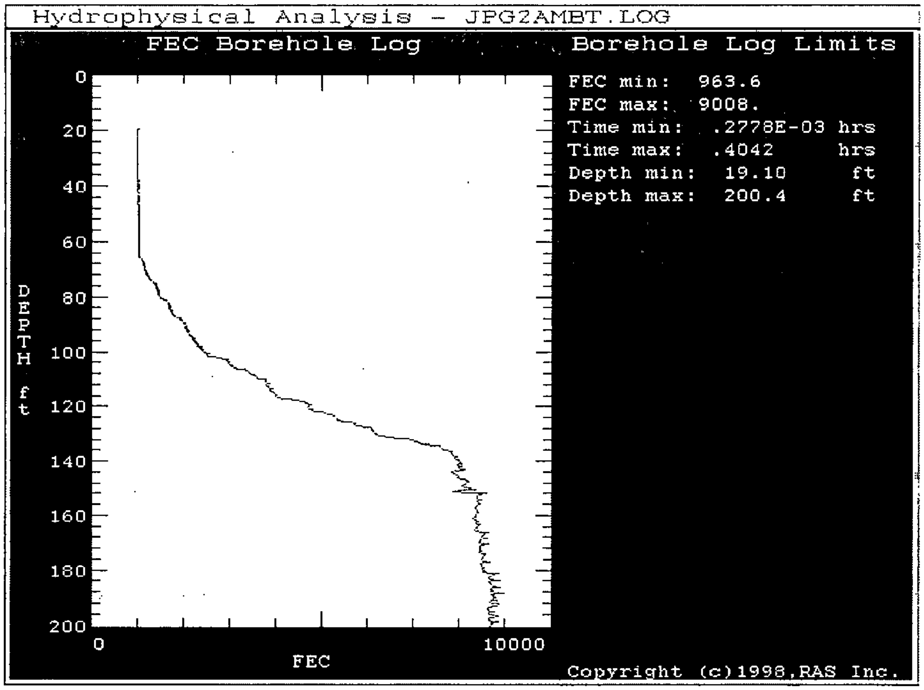


Figure 55. Background fluid-electrical-conductivity log for well JPG-2, Jefferson Proving Ground, Indiana.

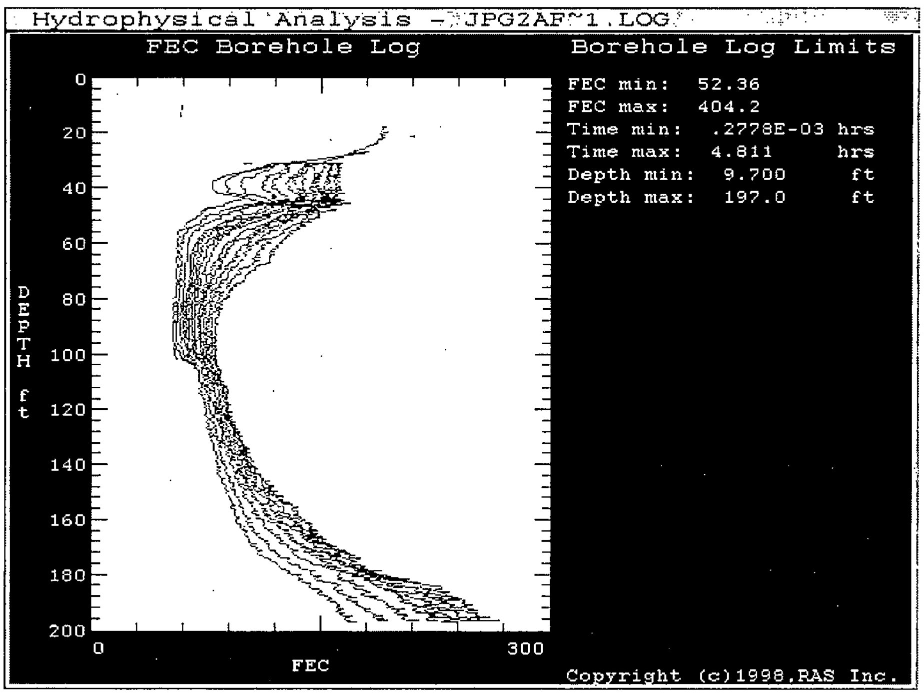


Figure 56. Hydrophysical log summary for well JPG-2, Jefferson Proving Ground, Indiana.

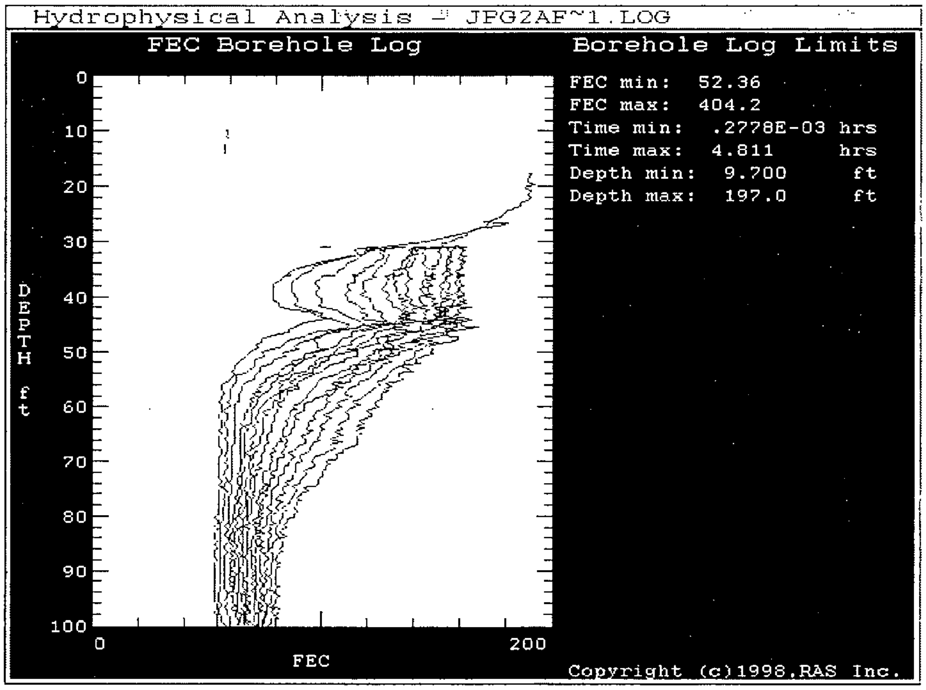
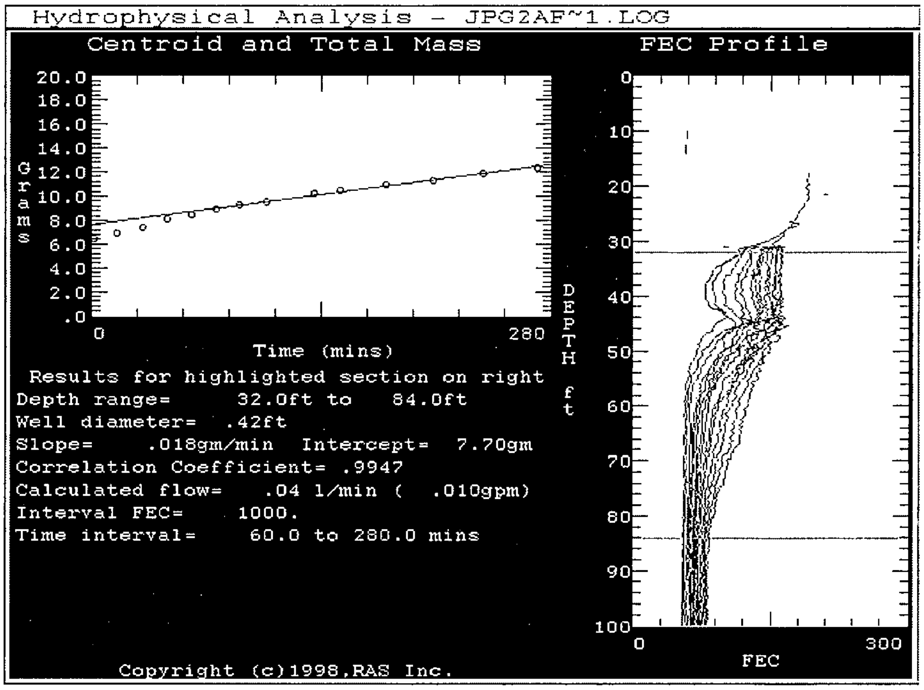


Figure 57. Hydrophysical log summary for the upper half of well JPG-2, Jefferson Proving Ground, Indiana.

well JPG-5, the FEC in the deeper part of well JPG-2 may be underestimated in this analysis, resulting in the horizontal flow being overestimated.

The day after well JPG-2 was logged under ambient conditions, it was logged again while nearby well JPG-1 was pumped at an average rate of 0.73 gal/min to induce ground-water flow to the pumped well. The drawdown curves for the two wells indicate that a water-level difference of about 11 ft was established between the two wells during the pumping (fig. 61, p. 96). The oscillating water levels in well JPG-2 are caused by the movement of the logging tool and cable in the well. The large rise in the water level prior to 10:00 is in response to placing the discharge pump and injection line into the well. The pump in well JPG-1 was started at 10:00, and the fluid emplacement in well JPG-2 was done from 12:00 to 12:40. Immediately following the fluid emplacement, a series of FEC logs were run over a time span of about 5 hours (fig. 62, p. 96). These logs suggest anomalies over the intervals 42 to 50 ft, 150 to 180 ft, and 180 to 196 ft. The interval of greatest interest is the upper half of the well and is shown at a larger scale in figure 63, p. 97. Mass-flux analysis and dilution analysis were completed for the intervals 42 to 50 ft, 150 to 180 ft, and 180 to 196 ft to calculate the volumetric inflow to the well and the velocity in the borehole. The mass-flux analysis for the upper interval 42 to 50 ft indicated a volumetric inflow rate of 0.003 gal/min, and the dilution analysis indicated a velocity in the borehole of 0.34 ft/d (fig. 64, p. 98, and table 23). The mass-flux analysis for the test interval 150 to 180 ft indicated a volumetric inflow rate of 0.003 gal/min, and the dilution analysis indicated a velocity in the borehole of 0.43 ft/d (fig. 65). The mass-flux analysis for the lower interval 180 to 196 ft indicated a volumetric inflow rate of 0.003 gal/min, and the dilution analysis indicated a velocity in the bore-



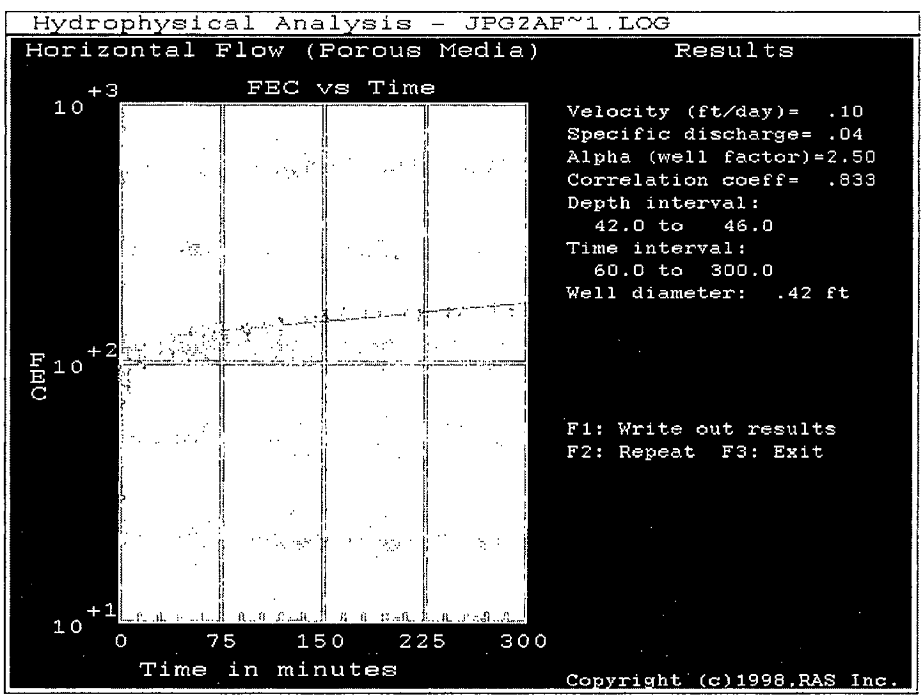
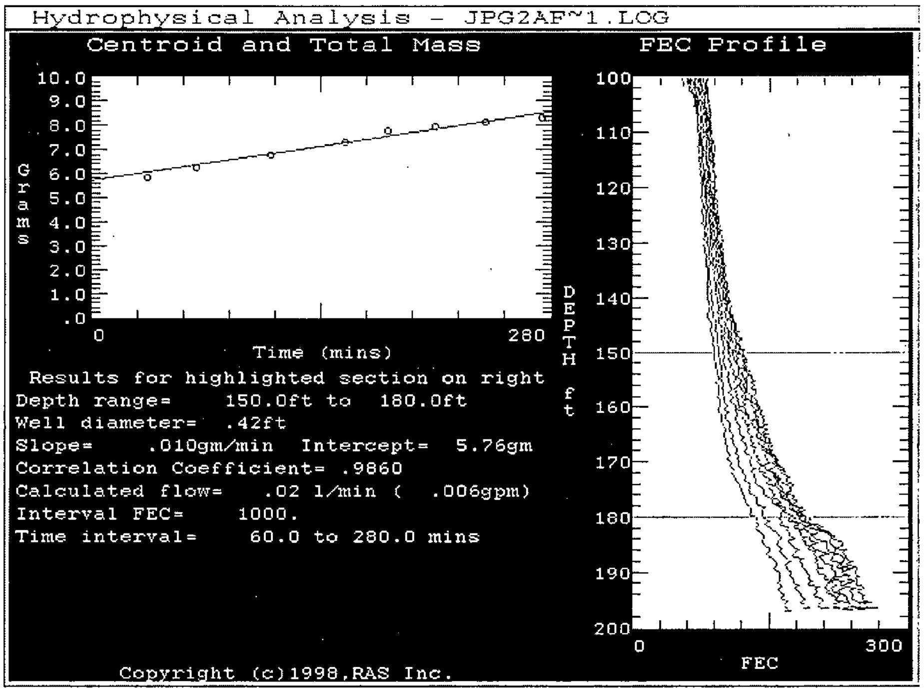


Figure 58. Results of mass-flux analysis and dilution analysis for the test interval 42 to 46 feet in well JPG-2, Jefferson Proving Ground, Indiana.



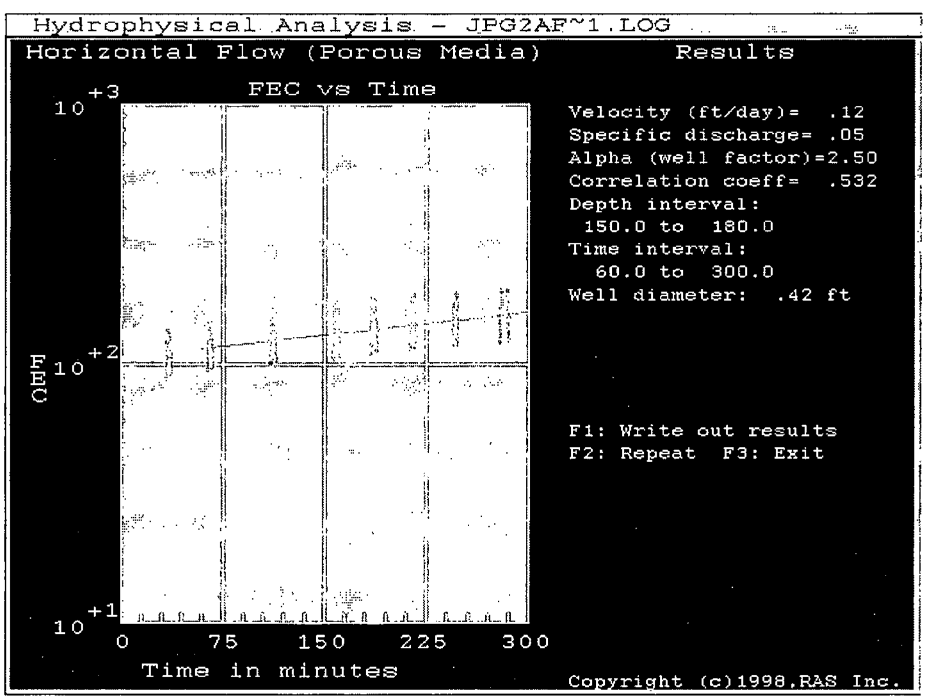
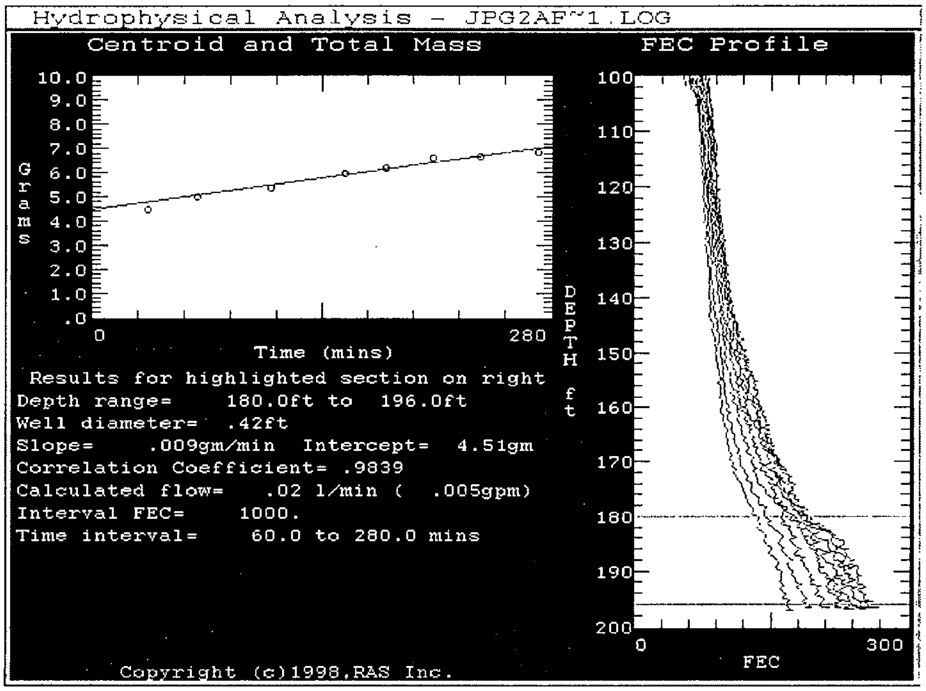


Figure 59. Results of mass-flux analysis and dilution analysis for the test interval 150 to 180 feet in well JPG-2, Jefferson Proving Ground, Indiana.



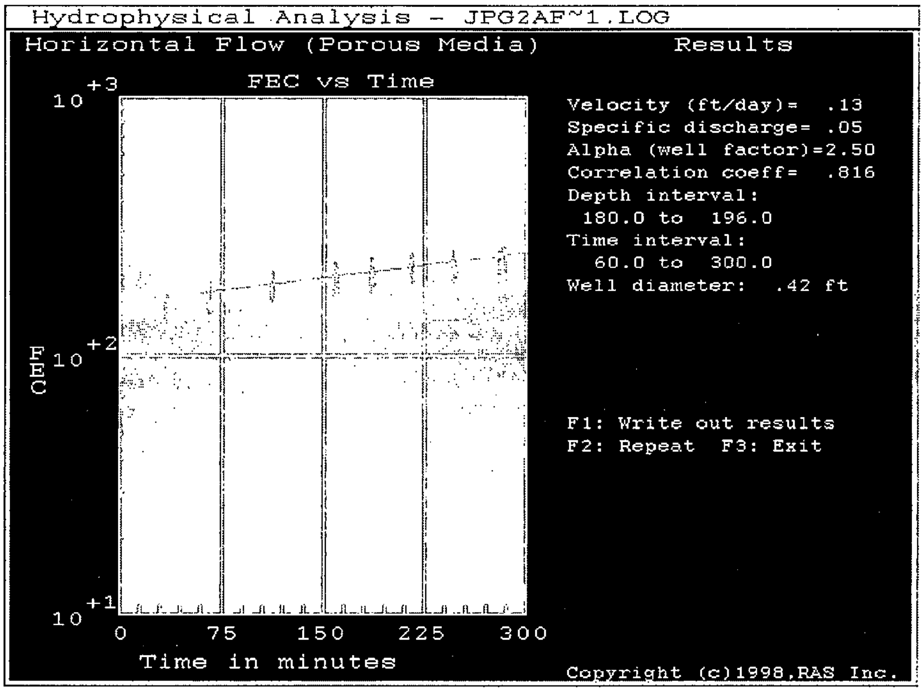


Figure 60. Results of mass-flux analysis and dilution analysis for the test interval 180 to 196 feet in well JPG-2, Jefferson Proving Ground, Indiana.

hole of 0.36 ft/d (fig. 66, p. 100). The volumetric-inflow rates for these test intervals may be below the reasonable minimum for the integral-method algorithm used in the mass-flux analysis.

A comparison of the velocities in the borehole under ambient conditions and while pumping well JPG-1 suggests that the three test intervals are hydraulically connected between the two wells. The velocity in the borehole during the pumping was about 3 times the velocity during ambient conditions for the test intervals (table 23).

The wells at Fort Campbell were logged September 20–24, starting with well FC-29. The static water level was at 40.2 ft below the top of casing, and the bottom of casing was at 44.0 ft. The background FEC log at well FC-29 showed a sharp increase in FEC at the two open fractures (fig. 67, p. 101). The base of the upper fracture was at a depth of about 68.1 ft, and the base of the lower fracture was at a depth of about 92.1 ft (determined with a borehole camera). The June vertical-flow logging indicated vertical flow from the upper fracture to the lower fracture under ambient conditions (fig. 11).

During fluid emplacement, approximately 29 gal of deionized water were lost to the formation. The water level returned to the static level within 15 minutes after completing the fluid emplacement. Immediately following the fluid emplacement, a series of FEC logs were run for the hydrophysical analysis (fig. 68, p. 102). These logs indicate an anomaly over the interval 50 to 100 ft and suggest downward vertical flow over the interval 69 to 93 ft. Mass-flux analysis was completed for the interval 55 to 155 ft to calculate the inflow rate for the upper fracture (fig. 69). The FEC of the formation water for the mass-flux analysis was estimated as 400 μS/cm and was based on the background FEC log. The mass-flux analysis for the interval 68 to 70 ft, just below the upper fracture, indicated a volumetric inflow rate of 0.21 gal/min. This calculation of the vertical flow is consistent with the June vertical-flow measurements, which averaged about 0.15 gal/min of downward flow (fig. 11).

The observation of strong downward flow eliminated the possibility of measuring horizontal flow in the fluid column of the open borehole. The following day, a single packer equipped with a differential-pressure transducer was used to cut off the vertical flow in the borehole, which allowed horizontal flow to establish in the upper fracture. The packer is a prototype wireline packer developed by the USGS. The development and application of the packer are described by Paillet and others (1998).

The packer was set at a depth of 89 ft, and the heads were allowed to stabilize. After about 45 minutes, the head difference between the two zones (above and below the packer) stabilized at approximately 0.47 ft. The positive head difference indicates that the zone above the packer has a higher head than the zone below the packer, which is what drives the downward flow in the borehole. This head difference is consistent with the 0.5 ft of head modeled for the June vertical-flow logging (table 1).

After the head difference had stabilized, the fluid emplacement was completed for the part of the borehole above the packer. During the fluid emplacement, approximately 2 gal of deionized water were lost to the formation. The water level returned to within 0.2 ft of the static water level within 30 minutes of completing the emplacement. Immediately following the fluid emplacement, a series of FEC logs were run (fig. 70, p. 103). These logs suggest horizontal flow is occurring in the interval 68 to 78 ft. Mass-flux analysis and dilution analysis were completed for this interval to calculate the volumetric inflow rate and velocity in the borehole. The mass-flux analysis for the test interval 68 to 78 ft indicated a volumetric inflow rate of 0.021 gal/min, and the dilution analysis indicated a velocity in the borehole of 0.77 ft/d (fig. 71 and table 23).

The hydrophysical logging at well FC-15 began on September 22. The static water level was at 91.1 ft below the top of casing, and the bottom of casing was at 88.3 ft. The background (pre-emplacement) FEC log did not show a change in FEC at the open fractures as in well FC-29 (fig. 72, p. 105). During fluid emplacement,

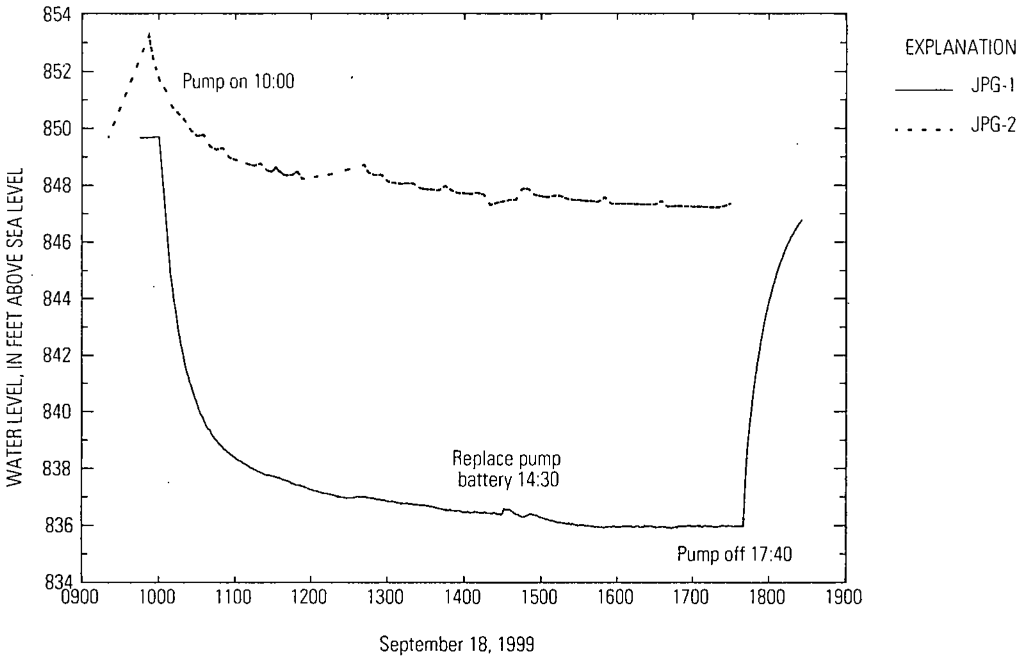


Figure 61. Drawdown curves for well JPG-2 and nearby well JPG-1, which was pumped at 0.73 gallon per minute, while hydrophysical logging was done in well JPG-2, Jefferson Proving Ground, Indiana.

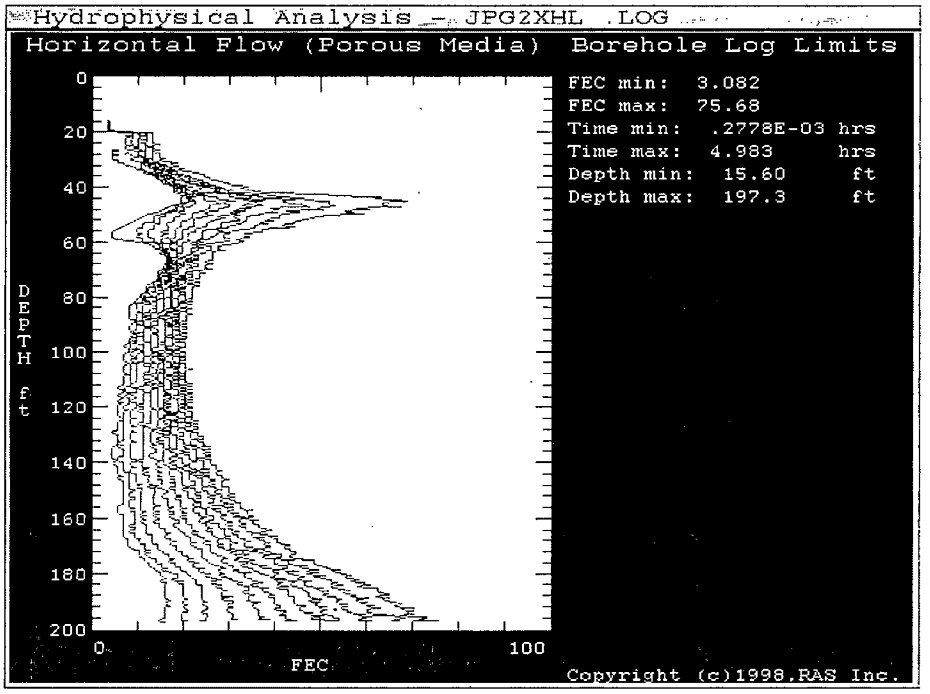


Figure 62. Hydrophysical log summary for well JPG-2 while pumping nearby well JPG-1, Jefferson Proving Ground, Indiana.

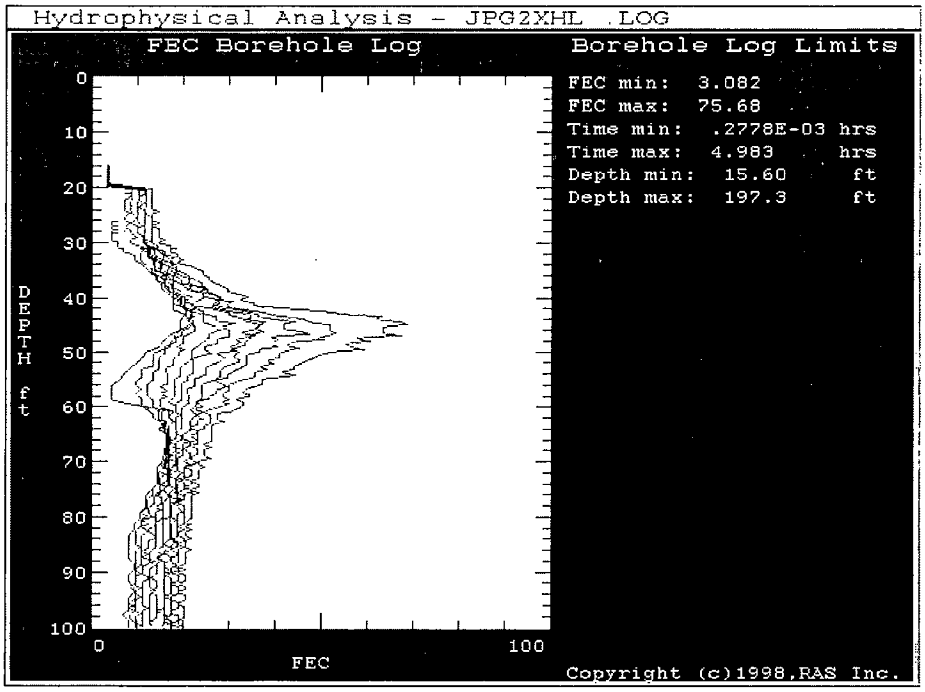


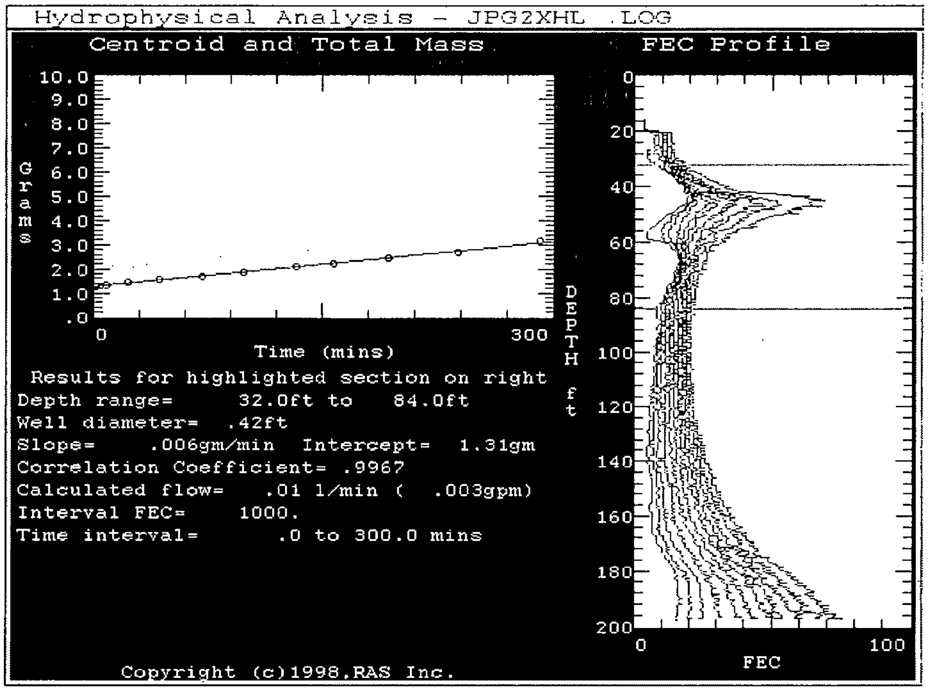
Figure 63. Hydrophysical log summary for the upper half of well JPG-2 while pumping nearby well JPG-1, Jefferson Proving Ground, Indiana.

approximately 40 gal of deionized water were lost to the formation. The water level returned to within 0.3 ft of the static water level within 20 minutes after the emplacement. Immediately following the fluid emplacement, a series of FEC logs were run for the hydrophysical analysis (fig. 73, p. 105). These logs suggested an FEC anomaly over the interval 125 to 159 ft. Inflow occurs along the interval 142 to 147 ft, from which there is vertical flow upward and downward in the borehole.

Mass-flux analysis was performed to calculate the vertical-flow rates in the borehole. The FEC of the formation water for the mass-flux analysis was estimated as 760 μS/cm and was based on the background FEC log. The mass-flux analysis for the interval 112 to 159 ft indicated a volumetric inflow rate to the well of 0.62 gal/min, which would be the flow entering the well at the second fracture (fig. 74). The mass-flux analysis for the interval above the second fracture indicated a vertical-flow rate of 0.161 gal/min, which would be the flow moving up the borehole and exiting at the first fracture (fig. 75). The mass-flux analysis for the interval below the second fracture indicated a vertical-flow rate of 0.386 gal/min, which would be the flow moving down the borehole and exiting at the third fracture (fig. 76, p. 107).

The interpretation of the vertical flow in the borehole is based on a combination of the hydrophysical logging and the information gained from the background geophysical logging. The background geophysical logging provided the location of the three open fractures by use of the caliper and acoustic-televiewer logs. The vertical-flow logging identified vertical flow in the borehole under ambient conditions.

The vertical-flow logging indicated that the middle fracture was a thieving zone, with strong downward flow from the upper fracture and slight upward flow from the lower fracture (fig. 12).



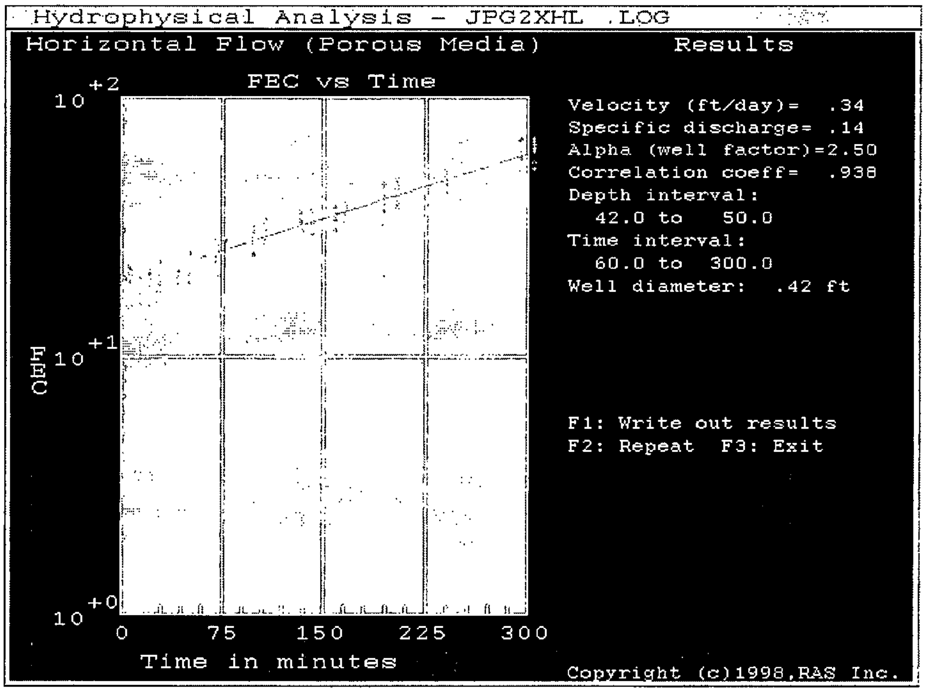
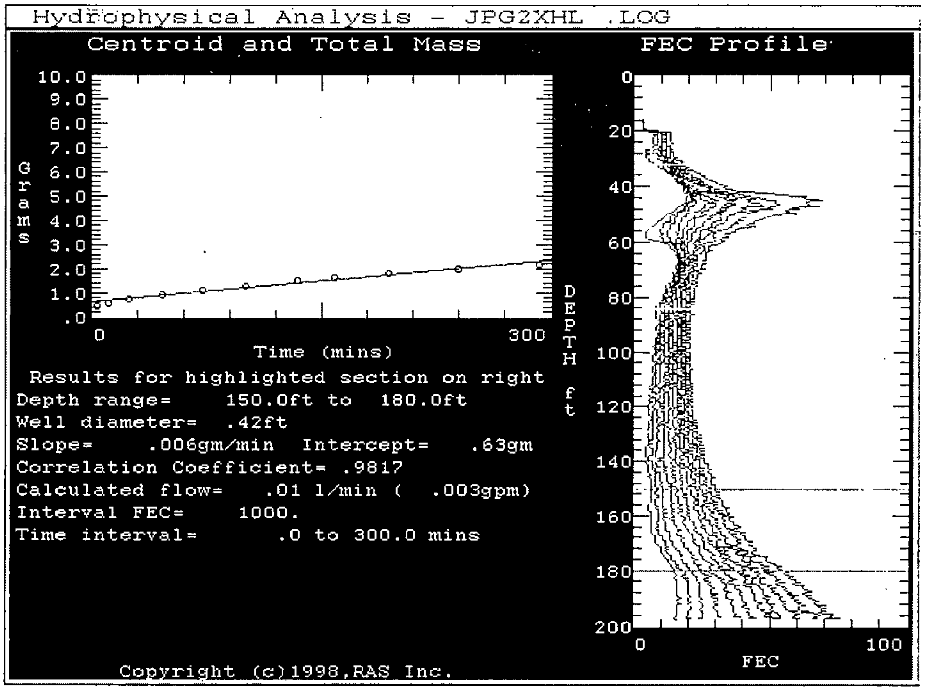


Figure 64. Results of mass-flux analysis and dilution analysis for the test interval 42 to 50 feet in well JPG-2 while pumping nearby well JPG-1, Jefferson Proving Ground, Indiana.



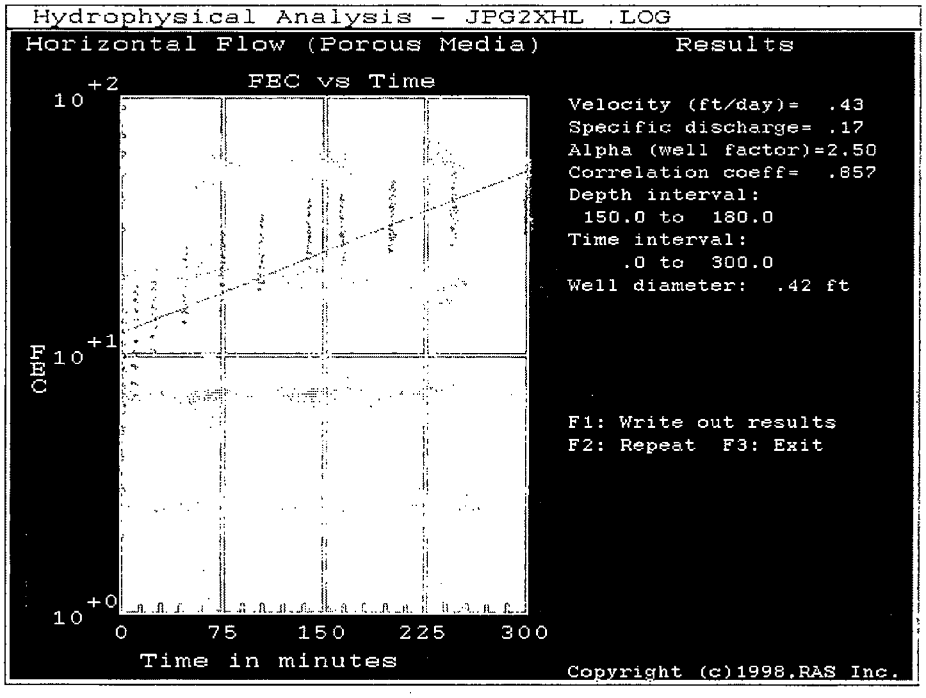
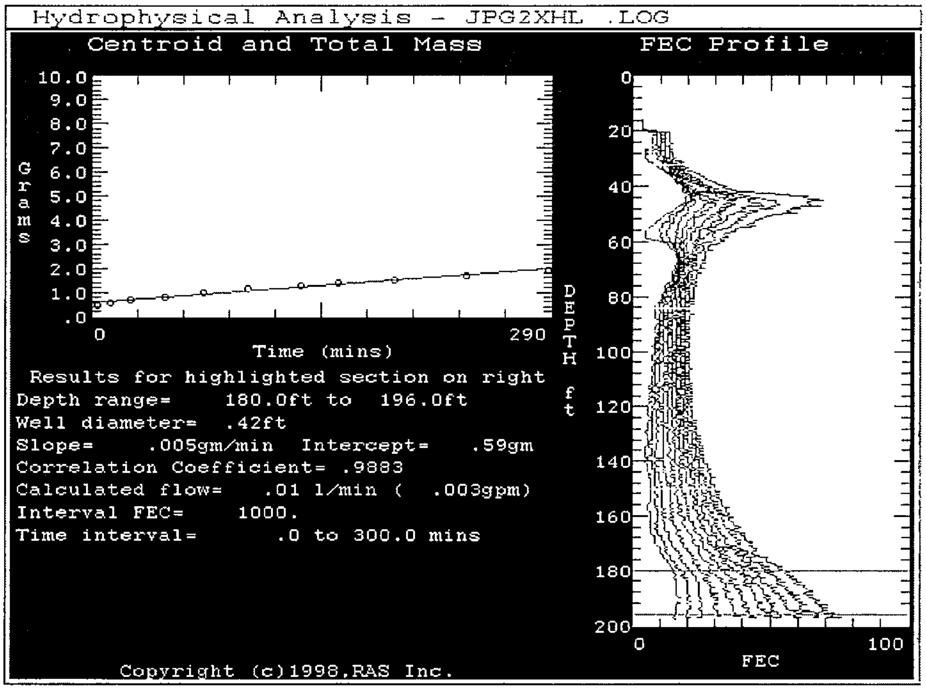


Figure 65. Results of mass-flux analysis and dilution analysis for the test interval 150 to 180 feet in well JPG-2 while pumping nearby well JPG-1, Jefferson Proving Ground, Indiana.



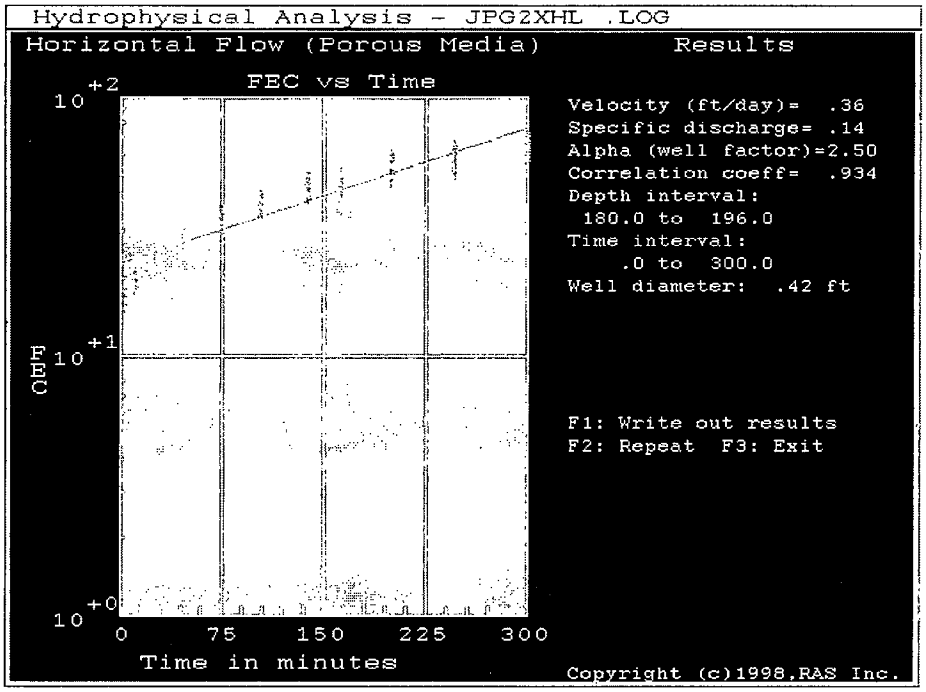


Figure 66. Results of mass-flux analysis and dilution analysis for the test interval 180 to 196 feet in well JPG-2 while pumping nearby well JPG-1, Jefferson Proving Ground, Indiana.

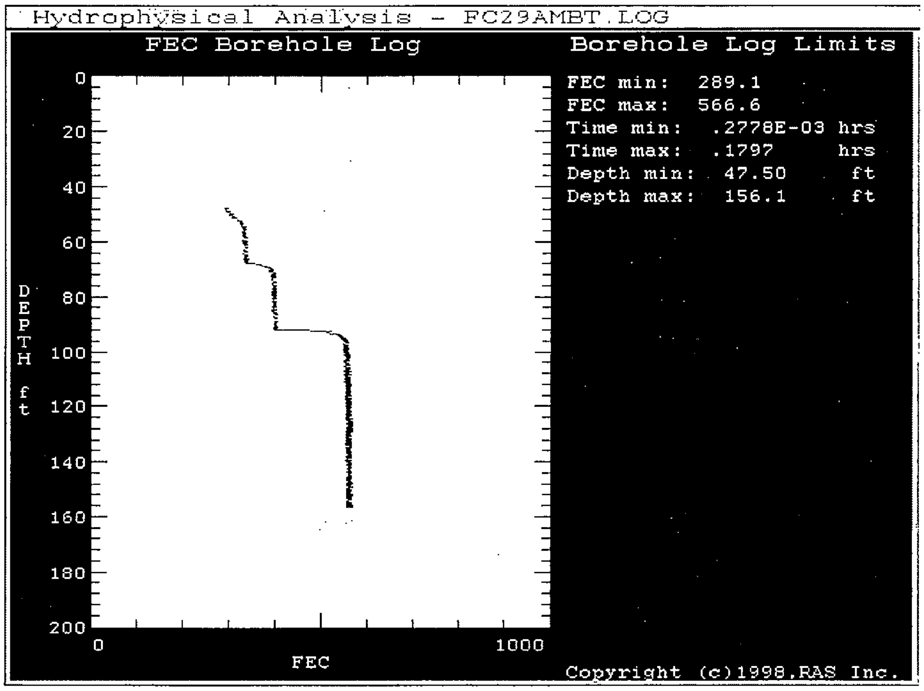


Figure 67. Background fluid-electrical-conductivity log for well FC-29, Fort Campbell, Kentucky.

The static water level during the June background logging was at 85.2 ft, almost 6 ft higher than during the hydrophysical logging. Apparently, the drop in water level caused a reversal in the vertical head gradients—the second fracture became the producing zone, and the upper and lower fractures became thieving zones.

The observation of strong vertical flow in the borehole eliminated the possibility of measuring horizontal flow in the fluid column of the open borehole. The following day, the wireline packer was used to cut off the vertical flow in the borehole to allow for horizontal flow in the upper fracture. The packer was set at a depth of 139 ft, placing it above the second fracture. After about 30 minutes, the head difference between the two zones (above and below the packer) stabilized at approximately -0.34 ft. The negative head difference indicates the zone below the packer has a higher head than the zone above the packer. This head difference cannot be compared to the head difference modeled for the vertical-flow-logging results (table 1) because of the reversal in vertical head gradient.

After the head difference had stabilized, the fluid emplacement was completed for the part of the borehole above the packer. Immediately following the fluid emplacement, a series of FEC logs were run (fig. 77). These logs suggest horizontal flow is occurring in the intervals 102 to 119 ft and 130 to 137 ft. Mass-flux analysis and dilution analysis were completed for these intervals to calculate the volumetric inflow rates and velocities in the borehole. The mass-flux analysis for the test interval 102 to 119 ft indicated a volumetric inflow rate of 0.014 gal/min, and the dilution analysis indicated a velocity in the borehole of 0.71 ft/d (fig. 78, p. 108, and table 23). The mass-flux analysis for the test interval 130 to 137 ft indicated a volumetric inflow rate of 0.003 gal/min, and the dilution analysis indicated a velocity in the borehole of 0.93 ft/d (fig. 79). The volumetric

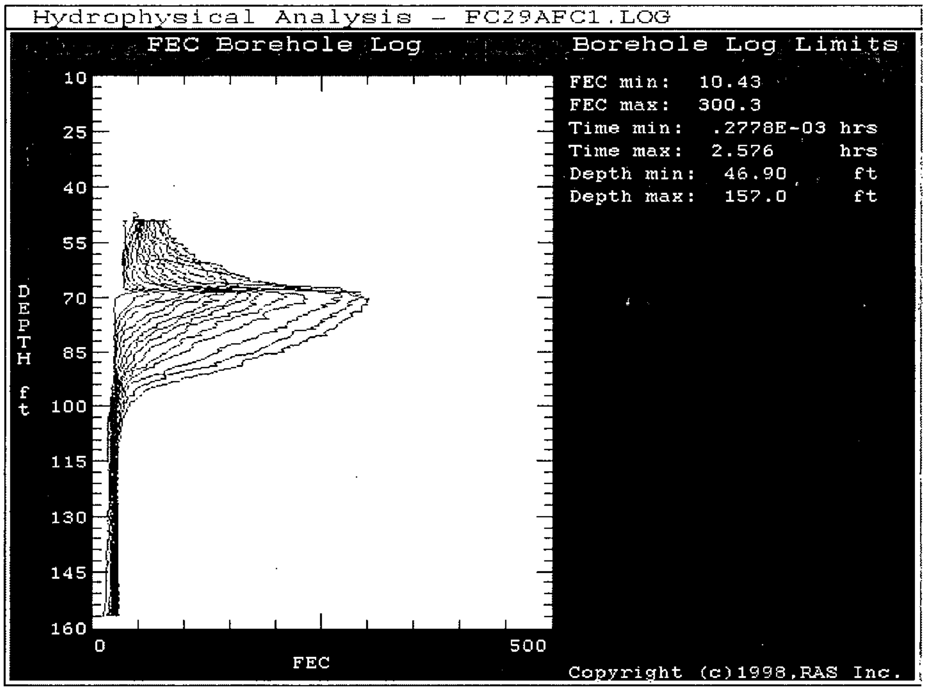


Figure 68. Hydrophysical log summary for the open-hole conditions in well FC-29, Fort Campbell, Kentucky.

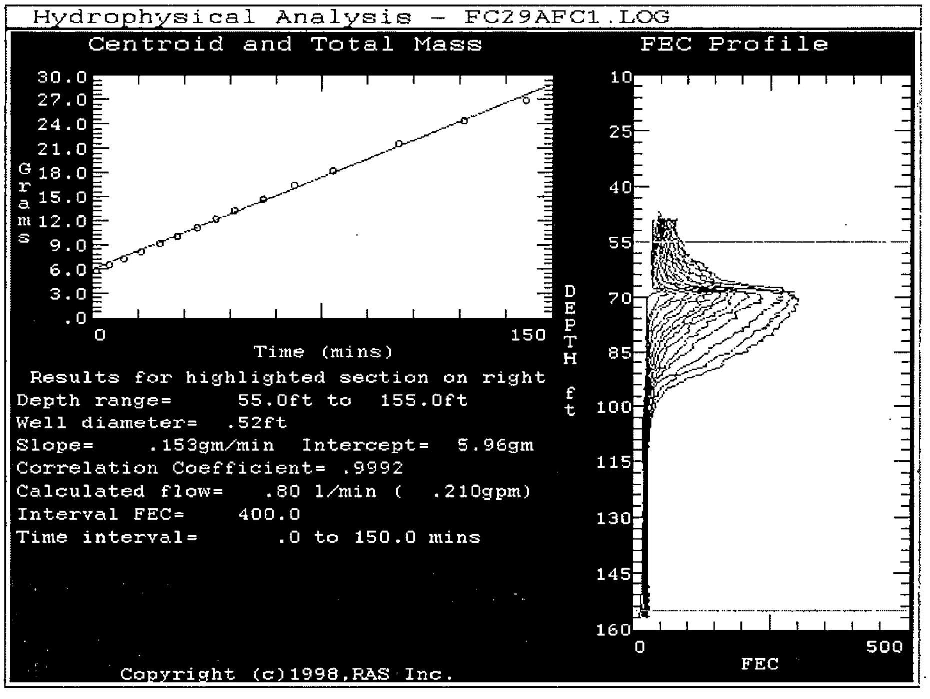


Figure 69. Results of mass-flux analysis for calculating vertical flow in well FC-29, Fort Campbell, Kentucky.

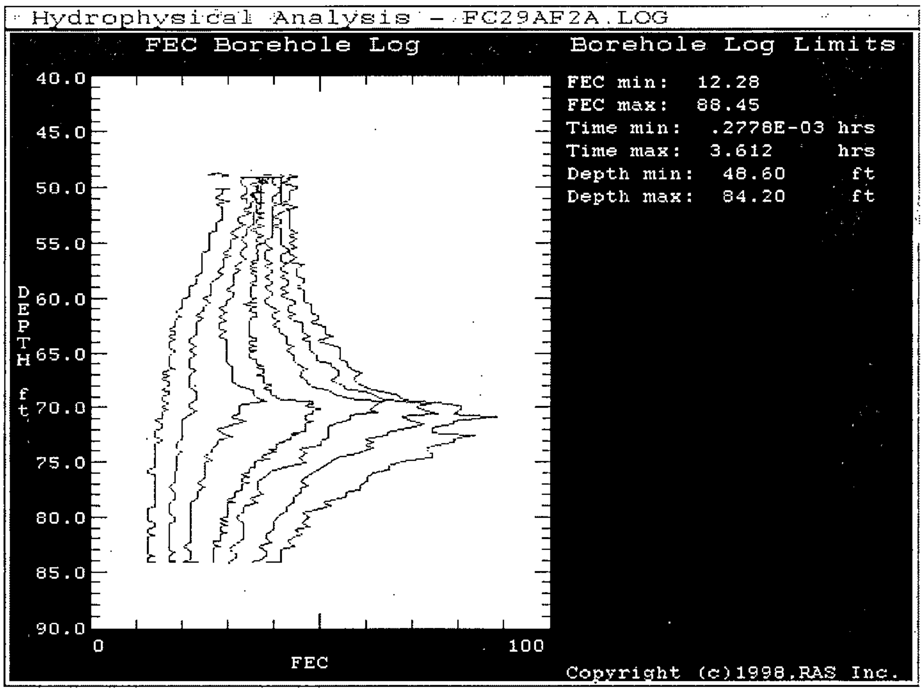
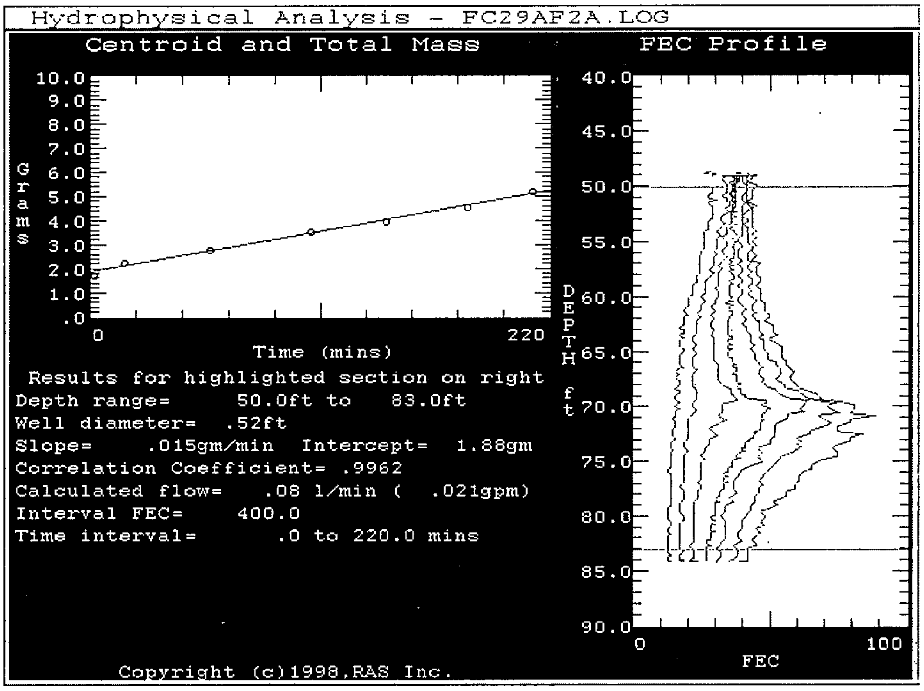


Figure 70. Hydrophysical log summary for well FC-29 with a packer set at 89 feet, Fort Campbell, Kentucky.

inflow rate of 0.003 gal/min for the interval 130 to 137 ft is low and, although detectable with the hydrophysical logging tool, the mass-flux analysis may not be appropriate for such low-flow conditions. Neither of these two horizontal-flow zones include the upper fracture (centered at a depth of about 128.5 ft), which suggests the horizontal flow must be occurring in smaller bedding-plane fractures above and below the visibly open fracture.

The hydrophysical logging at well FC-16 was done on September 24. The static water level was at 55.9 ft below the top of casing, and the bottom of casing was at 47.2 ft. The background FEC log did not show a change in FEC at the open fracture, which is at a depth of 81 ft (fig. 80, p. 110). During fluid emplacement, approximately 53 gal of deionized water were lost to the formation. The water level returned to within 0.6 ft of the static level within 90 minutes after the fluid emplacement. Immediately following the fluid emplacement, a series of FEC logs were run for the hydrophysical analysis (fig. 81). These logs suggest an FEC anomaly over the interval 60 to 100 ft. Flow enters the well over the interval 60 to 66 ft and flows downward with no obvious exit point, even though the open fracture is at 81 ft.

Mass-flux analysis was completed to determine the vertical-flow rate. The FEC of the formation water for the mass-flux analysis was estimated as 710 μS/cm and was based on the background FEC log. The mass-flux analysis indicated a downward volumetric flow rate of 0.023 gal/min (fig. 82, p. 111). The observation of downward flow eliminated the possibility of measuring horizontal flow in the fluid column of the open borehole. Time did not permit the installation of the wireline packer and additional logging at this well. The vertical-flowmeter work during June did not detect vertical flow in this well under ambient conditions (fig. 13). The vertical flow detected by the hydrophysical logging may be below the resolution of the vertical heat-pulse flowmeter. Because hydrophysical logging provides a complete depth profile of the borehole, a



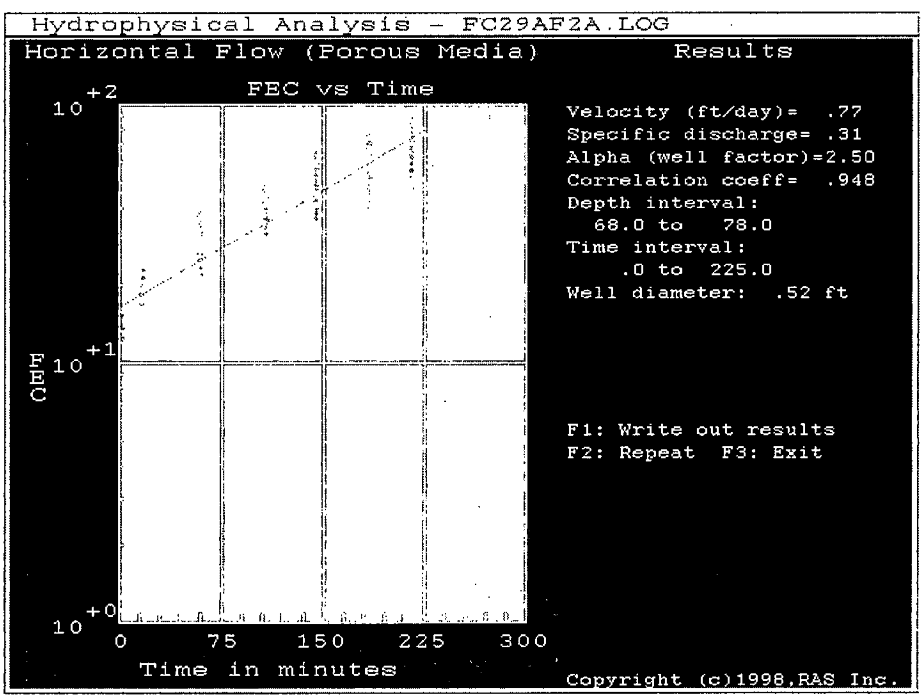


Figure 71. Results of mass-flux analysis and dilution analysis for the test interval 68 to 78 feet with a packer set at 89 feet in well FC-29, Fort Campbell, Kentucky.

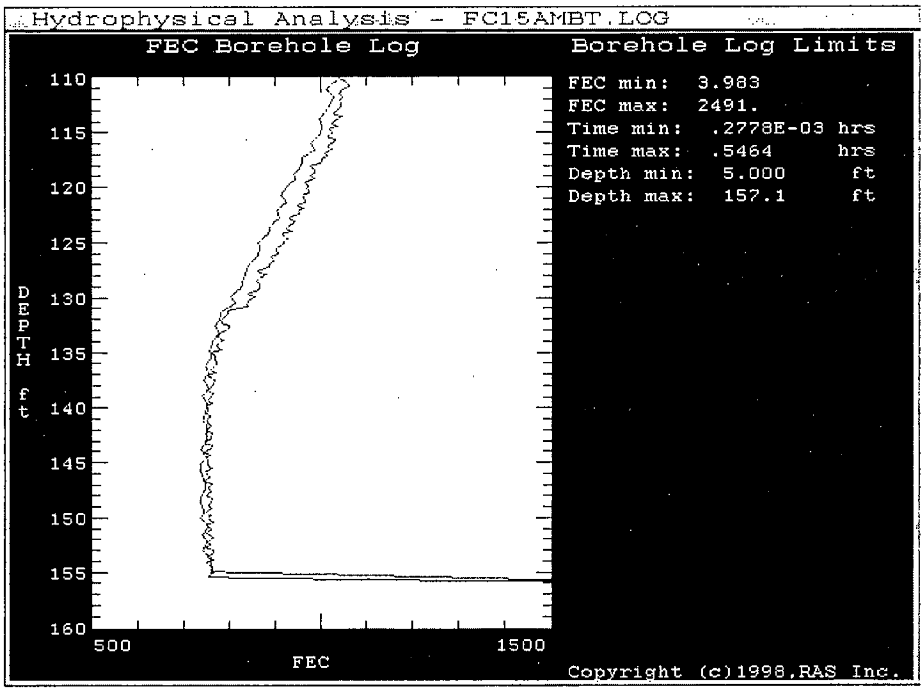


Figure 72. Background fluid-electrical-conductivity log for well FC-15, Fort Campbell, Tennessee.

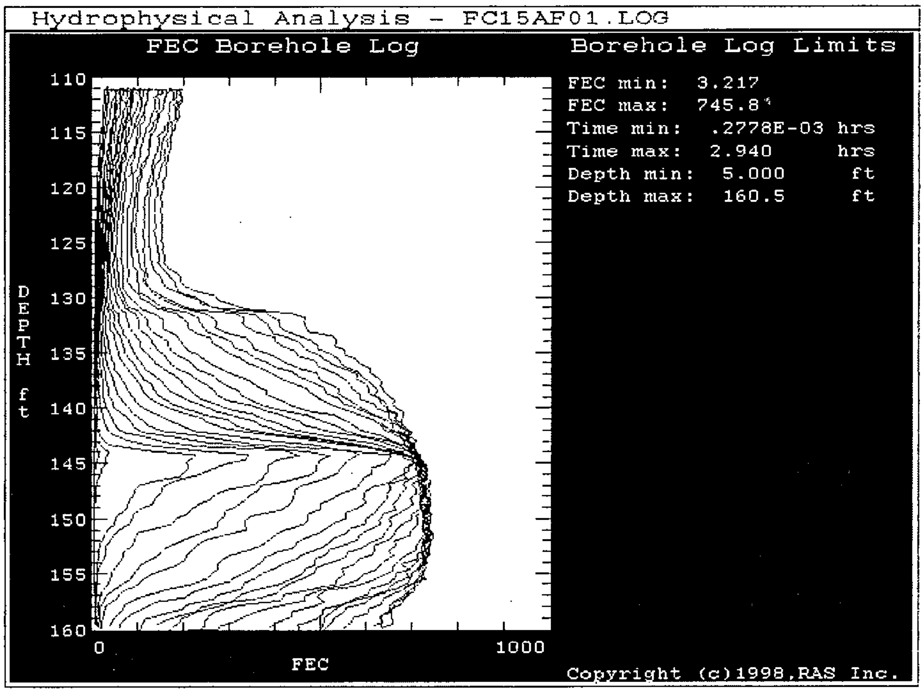


Figure 73. Hydrophysical log summary for the open-hole conditions in well FC-15, Fort Campbell, Tennessee.

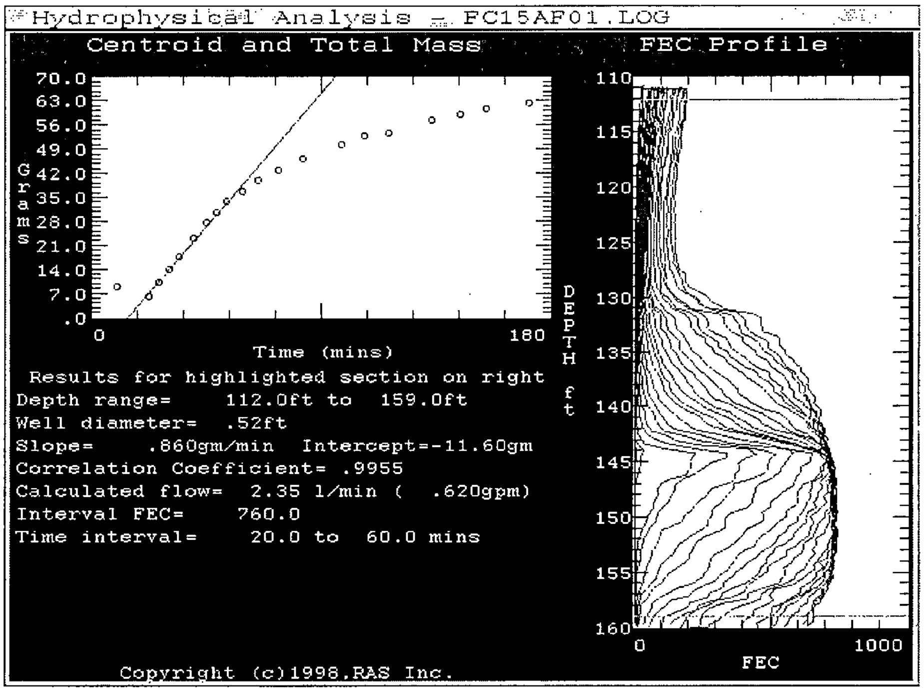


Figure 74. Results of mass-flux analysis for calculating vertical flow in well FC-15, Fort Campbell, Tennessee.

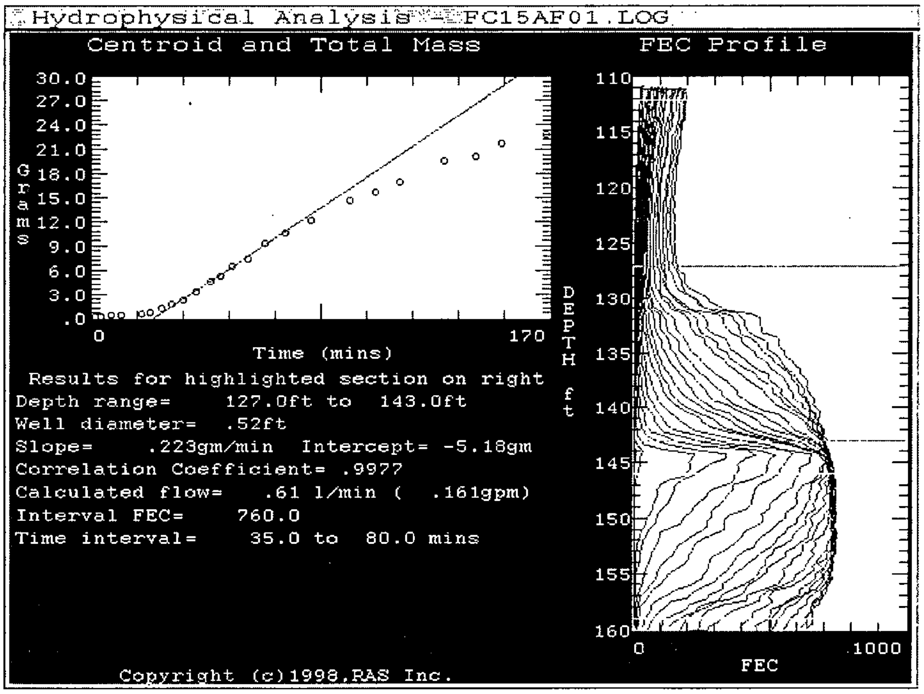


Figure 75. Results of mass-flux analysis for calculating vertical flow above the second fracture in well FC-15, Fort Campbell, Tennessee.

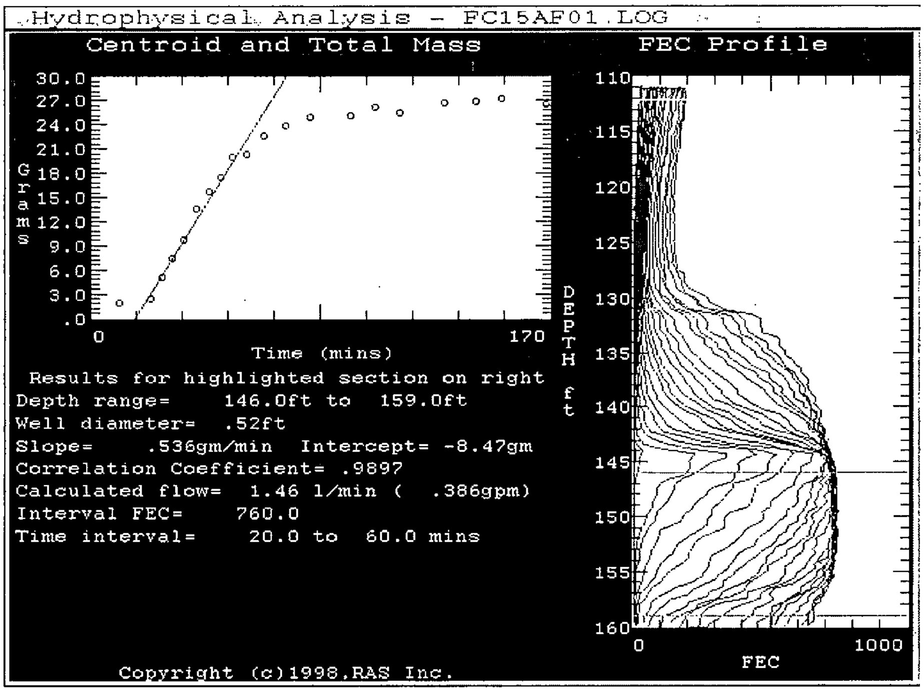


Figure 76. Results of mass-flux analysis for calculating vertical flow below the second fracture in well FC-15, Fort Campbell, Tennessee.

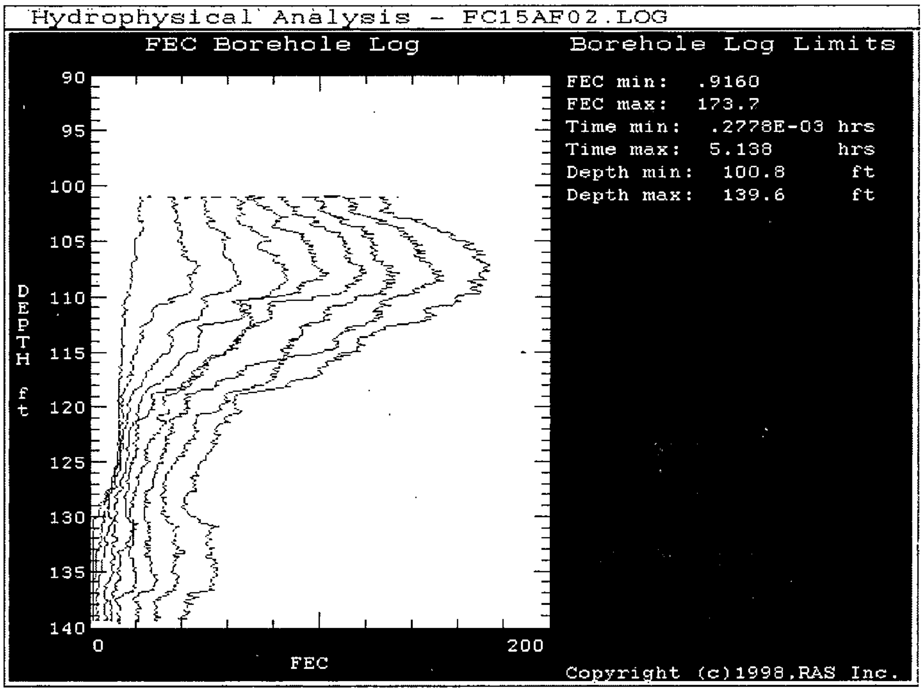
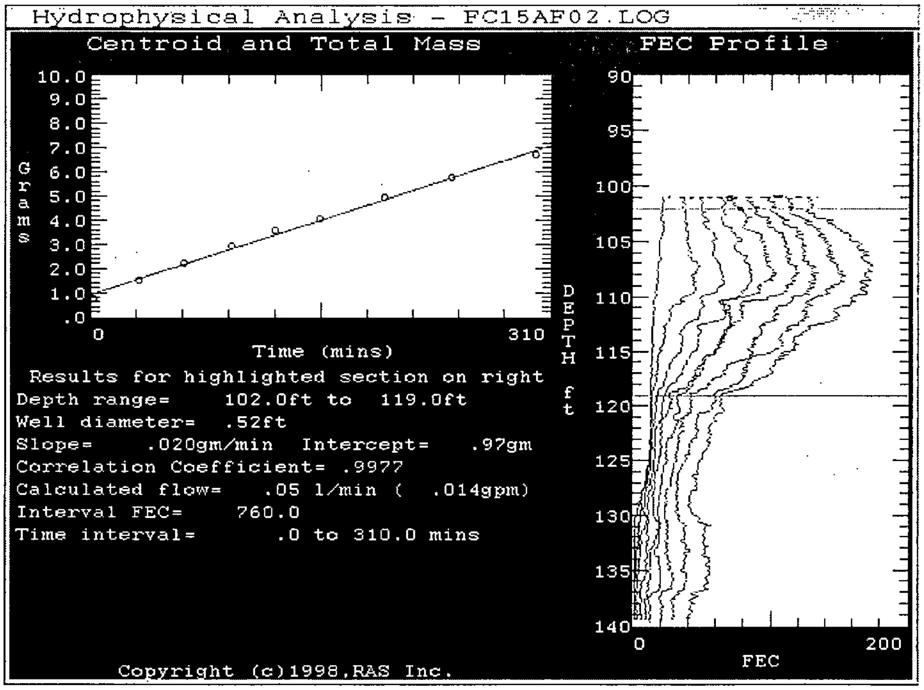


Figure 77. Hydrophysical log summary for well FC-15 with a packer set at 139 feet, Fort Campbell, Tennessee.



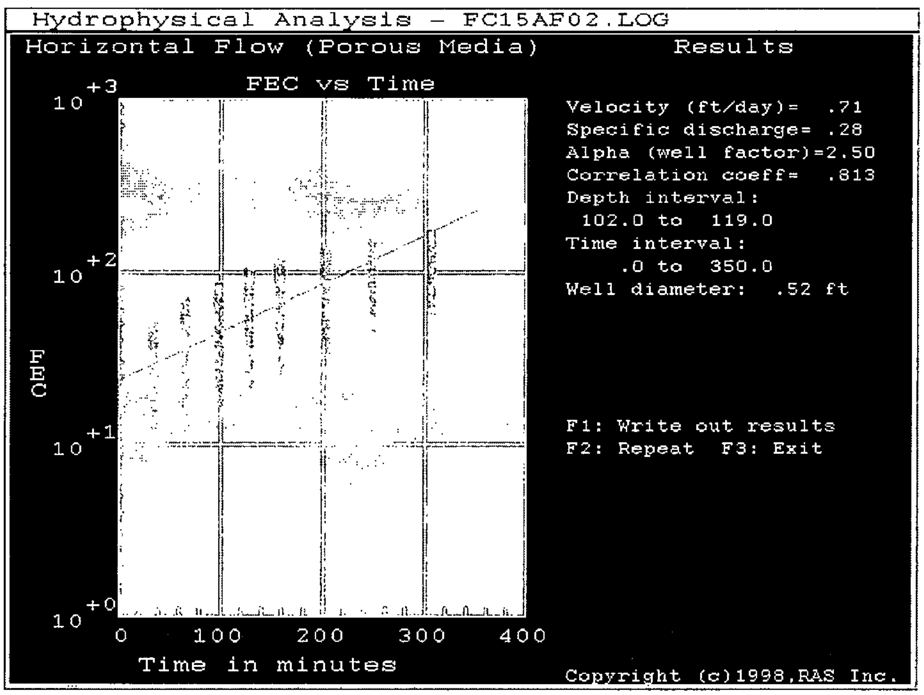
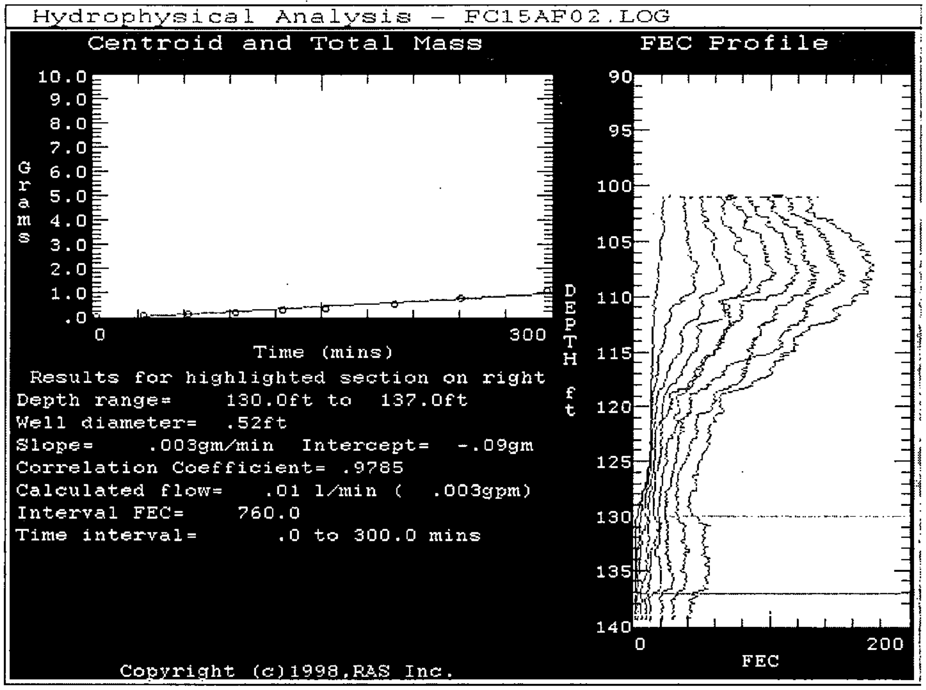


Figure 78. Results of mass-flux analysis and dilution analysis for the test interval 102 to 119 feet with a packer set at 139 feet in well FC-15, Fort Campbell, Tennessee.



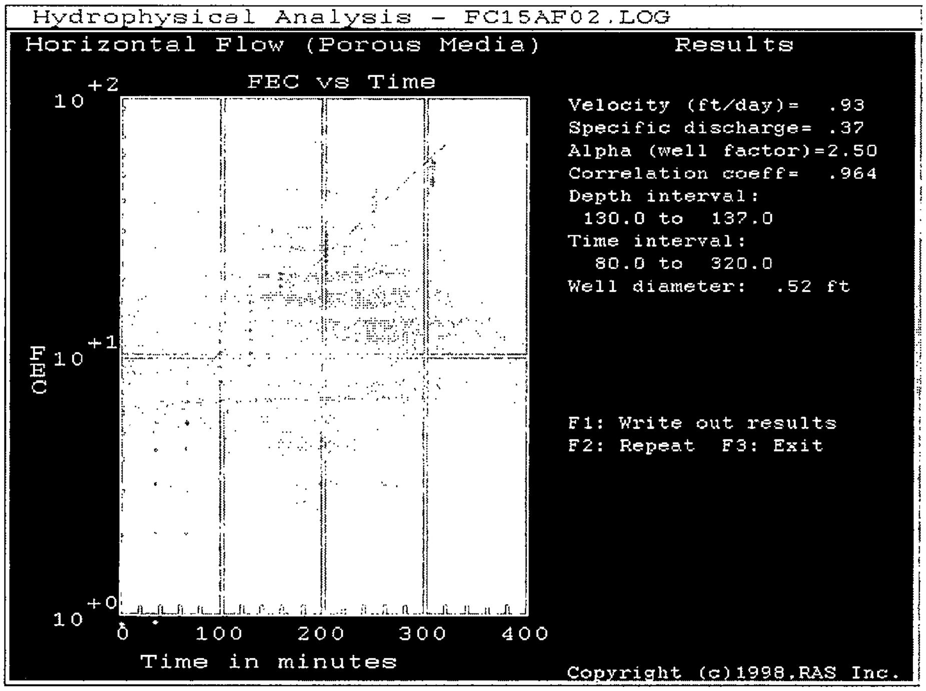


Figure 79. Results of mass-flux analysis and dilution analysis for the test interval 130 to 137 feet with a packer set at 139 feet in well FC-15, Fort Campbell, Tennessee.

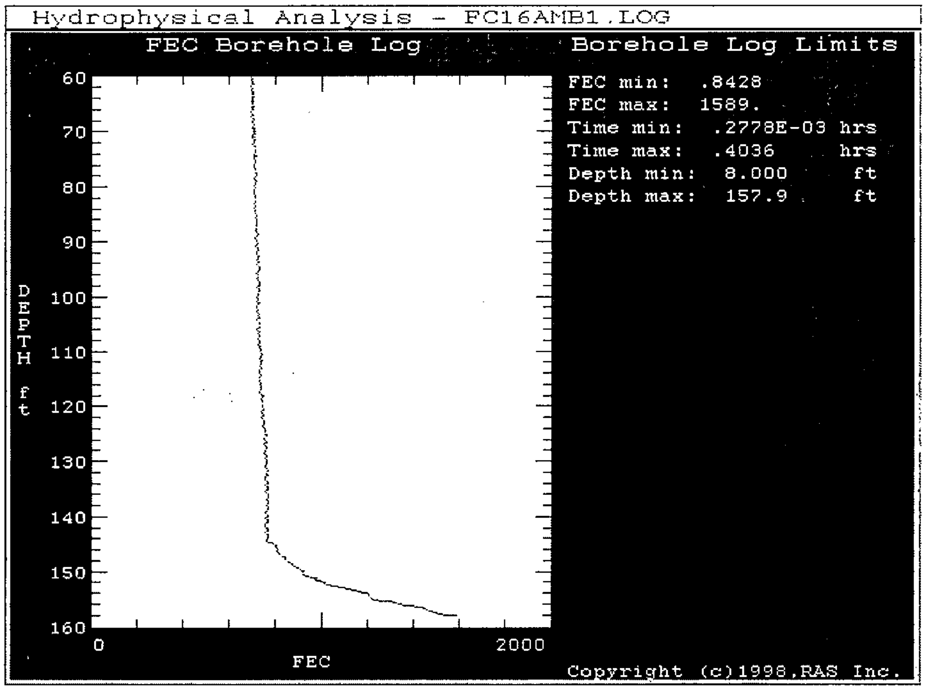


Figure 80. Background fluid-electrical-conductivity log for well FC-16, Fort Campbell, Kentucky.

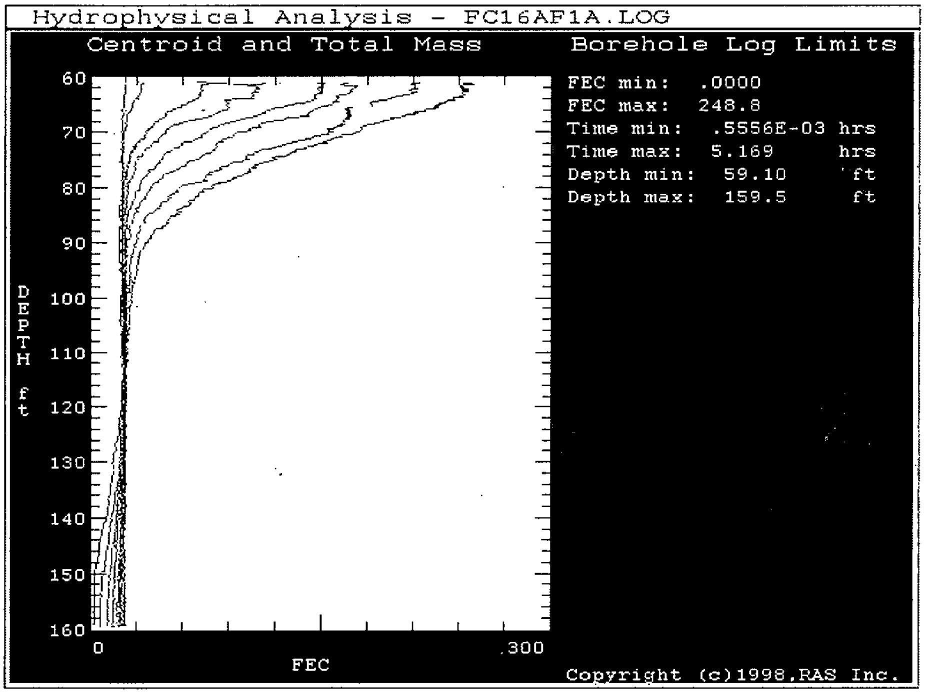


Figure 81. Hydrophysical log summary for the open-hole conditions in well FC-16, Fort Campbell, Kentucky.

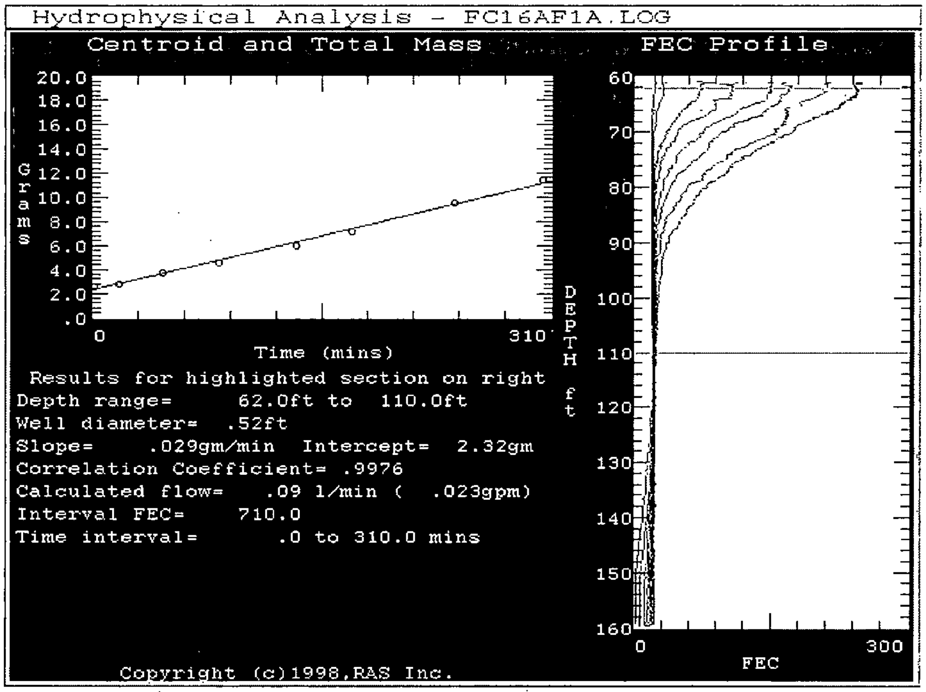


Figure 82. Results of mass-flux analysis for calculating vertical flow in well FC-16, Fort Campbell, Kentucky.

strength of this technique is to resolve where flow zones are located in a well. Hydrophysical logging may be most applicable as a background logging or screening method in wells that have long intervals open to the aquifer. 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. As was demonstrated in this study, the hydrophysical logging also can identify vertical-flow zones in wells where it may be necessary to use packer devices to obtain definitive measurements of the natural horizontal flow.

Comparison of the Flowmeter Methods

Each of the flowmeters used in this study has unique capabilities and limitations. Some distinguishing characteristics that could help future studies select a flowmeter method are discussed here and listed in table 24. The following discussion is limited to information supplied by the contractors to the USGS and to observations during data collection for this study.

The KVA flowmeter, colloidal borescope, and hydrophysical logging systems are available through retail purchase and service contracts. The ADV is in the research stage of development; it is not available for retail purchase but may be available to research projects within government agencies.

Each flowmeter method has a distinct principle of operation that can affect how well the tool works in different environments. The KVA flowmeter emits a heat pulse and measures its dissipation. Environmental contaminants in a well can affect the thermal properties of water and may need to be considered. The ADV emits an acoustic

Table 24. General information on the borehole flowmeters and the flowmeter methods

[ft, foot; v, volt; DC, direct current; AC, alternating current; pc, personal computer; PVC, polyvinyl chloride; mm, millimeter; ft/d, foot per day; gal/min, gallon per minute]

	KVA flowmeter Model 40	Acoustic Doppler velocimeter	Colloidal borescope	Hydrophysical logging
Equipment available for purchase	Yes	No	Yes	Yes
Contract services available	Yes	No	Yes	Yes
Tool length	12 inches	48 inches	24 inches	40 to 110 inches
Tool diameter	1.65 inches	3 inches	1.7 inches	1.5 inches
Minimum well diameter	2 inches	3.5 inches	2 inches	2 inches
Deployment	Aluminum rods	Cable and drawworks	Cable-manual	Cable and drawworks
Vehicle-mounted drawworks	No	No or Yes	No	Yes or No
Minimum field crew	1 person	1 person	1 person	2 people
Maximum working depth	250 ft (10-ft rods) 450 ft (20-ft rods)	400 ft	1,000 ft	5,000 ft
Power source	18v DC-contained	110v AC for pc; 12v DC for drawworks	110v AC	110v AC
Requires pc in field	No	Yes	Yes	Yes
Vendor software required	No	Yes	Yes	Yes
Approximate set-up time	.5 hour	.5 hour	.5 hour	1 to 4 hours
Continuous borehole profile	No	No	No	Yes
Lab calibration required to solve for velocity	Yes	No	No	No
Field calibration required	No	No	No	Yes
Postprocessing required	Yes	Yes	No	Yes
Works in open borehole	Yes	Yes	Yes	Yes
Works in PVC screens	Yes	Yes	Yes	Yes
Works in stainless-steel screens	Yes	Yes	Yes	Yes
Measured volume in borehole	Approximately 1 cubic inch	.008 to .028 cubic inch	Field of view is 1.0 mm by 1.4 mm by .1 mm	Entire borehole diameter
Measures horizontal direction	Yes	Yes	Yes	No
Measures horizontal velocity	Yes	Yes	Yes	Yes
Method of orientation	Compass	Magnetometer	Magnetometer	None
Measures vertical direction	No	Yes	No	Yes
Measures vertical velocity	No	Yes	No	Yes, as volume
Measures three-dimensional flow	No	Yes	No	No
Theoretical measurement range	.1 to 500 ft/d	25.9 ft/d to 691,200 ft/d	Stagnant to 7,085 ft/d	.01 ft/d minimum velocity to 1,000+ gal/min of flow

signal and records the signal reflections from particles in the water column. The speed of sound in water is affected by the salinity and temperature of the water. If these characteristics change appreciably with depth, measurement accuracy could be affected. The colloidal borescope operates by visually tracking the natural colloids in the water column. A lack of colloids in the water column could reduce the quality of a measurement or prevent a measurement, if lacking completely. Hydrophysical logging measures fluid-electrical conductivity and, more specifically, the change in fluid-electrical conductivity over time. When deionized water is used for fluid emplacement, the natural formation water needs to provide enough contrast in conductivity to measure the enrichment of the borehole fluids with formation water.

The calibration procedures did not appreciably affect time spent in the field. As part of the data analysis, the KVA flowmeter is calibrated in the laboratory following every field excursion. The calibration is necessary to convert machine units of velocity in the borehole to actual velocity units. The velocity in the borehole also is corrected to the ground-water-seepage velocity in the aquifer. The accuracy of the colloidal borescope has been documented by work done at the Desert Research Institute (Kearl, 1997), but the calibration is not checked routinely. The orientation of the magnetometer in the colloidal borescope and ADV can be checked in the laboratory and in the field. The accuracy of the acoustic transmitter and receivers in the ADV are checked routinely. The ADV software requires values of temperature and specific conductance of the borehole fluids needed to compute the speed of sound in the borehole fluids. These values are measured on site prior to data collection. The specific conductance sensors on the hydrophysical logging tool are calibrated at each well to a range that brackets the conductivity of the borehole fluids. The tool calibration is rechecked after each well is logged.

Instrument portability varies widely for the flowmeter systems. The KVA flowmeter, ADV, and colloidal borescope were shipped to a staging area by air freight and transported to the study site in and operated from a standard minivan. The computer equipment for the hydrophysical logging was vehicle mounted, but a more portable system could be used if desired. The hydrophysical logging required a support trailer, as well as tanks and a truck for transporting deionized water. The ADV and hydrophysical logging required a cable drawworks. The ADV used a portable drawworks system, and the drawworks for the hydrophysical logging was mounted on a standard geophysical logging truck. The ADV and the hydrophysical logging, however, can use portable drawworks or vehicle-mounted drawworks. The wireline packer used in the study required a separate, portable drawworks and computer. Cables for the KVA flowmeter and colloidal borescope were wound on lightweight hand reels. The aluminum rods for the KVA flowmeter were stored and transported in a carrying case.

The KVA flowmeter operates with 18 volts of DC (direct current) power supplied by batteries in the control-panel box. The ADV, colloidal borescope, and hydrophysical logging require 110-volt AC (alternating current) power because they use computers for data acquisition and processing. The hydrophysical logging also needs AC power to operate the pumps for the fluid-management system. AC power can be supplied with a portable generator or through a power inverter attached to a car battery. The hydrophysical logging received AC power through a generator on the logging truck and a portable generator. The drawworks for the ADV was powered by a standard 12-volt battery. The drawworks with the hydrophysical logging was operated by power supplied by the logging truck.

The hydrophysical logging requirement for on-site availability of potable water may limit portability to some field sites. Where ground-water quality permits, water from the tested well can be deionized on site and reinjected to flood the borehole. For this study, approximately 550 gal of deionized water were produced from tap water and transported to each well. Deionized water requirements vary with each well, depending on well diameter and the depth of the water column. A general guideline for complete fluid emplacement is three well volumes.

Set-up times for the KVA flowmeter, ADV, and colloidal borescope generally required about half an hour. The set-up time for the hydrophysical logging was about 2 hours; this included on-site calibration of the probe, assembling and arranging the fluid-management equipment, making and hauling deionized water, and running a background FEC log. Set-up time would increase with well depth because it would take longer to run the background FEC log.

The time required to make a measurement with each tool varied. The time required for a measurement with any of the tools also varied with the flow conditions in the well; higher ground-water velocities can allow for quicker measurements. The KVA flowmeter typically required about 30 to 45 minutes for each measurement. Lower velocities required more time for the heat pulse to dissipate in the vicinity of the thermistors. The ADV typically required about 10 to 15 minutes for each measurement. The time required for measurements with the colloidal borescope ranged from about 15 minutes to 2 hours, depending on the flow conditions at the test interval. The colloidal-borescope system and the ADV provided continuous graphing of the flow direction and velocity data, which allowed the field technician to evaluate the measurement. If no apparent trends were visible in the data or if no colloids were detected on the view finder (for the colloidal borescope), the measurement would end and the tool could be moved to the next test interval. Where consistent direction and velocity data were recorded, the measurement could be extended to verify the flow conditions.

The hydrophysical logging required 1 day for each test at a given well. For example, at two of the Fort Campbell wells, it took 1 day to log the well under open-hole conditions and 1 day to log the well with a packer set in the well. As with the point-measurement methods, the time required for hydrophysical logging probably would decrease with higher ground-water velocities.

Borehole construction and environmental setting may affect the suitability of the site for some flowmeters. The KVA flowmeter, colloidal borescope, and hydrophysical logging can be operated in standard 2-inch-diameter monitoring wells. The outer diameter of the ADV housing limits the use of the ADV to 3.5-inch- and larger diameter wells. All of the tested systems can be operated in cased or uncased wells; the method of well construction and development and the characteristics of the well screen may affect the measurements. The magnetometers in the ADV and colloidal borescope will not work in regular steel, but they can function in nonmagnetic stainless steel. For accurate measurements, the KVA flowmeter requires a well screen or borehole wall that allows a sound seal with the fuzzy packer. Fuzzy packers must be custom built to match the diameter of the well. Environments with excessive surface vibrations may adversely affect the ADV and colloidal borescope by disturbing the water column in the well. All probes used in this study were constructed of stainless steel and other materials resistant in chemically corrosive environments.

The KVA flowmeter is affected by borehole enlargements that allow flow to bypass the fuzzy packer. The ADV and colloidal borescope should not be affected by borehole enlargements because they are sampling the velocity at the center of the borehole. The KVA flowmeter also is affected by borehole irregularities that catch on the fuzzy packer and make it difficult to lower the tool into the well.

All of the methods can be affected by vertical flow in the borehole while trying to make measurements of horizontal flow. The KVA flowmeter has a solid top to the fuzzy packer, so it potentially could baffle vertical flow in a well if the fuzzy packer fits snugly against the well screen or borehole wall. The ADV and colloidal borescope used a baffle/skirt to block the vertical flow in the wells; however, the effectiveness of these baffles is uncertain. The ADV was designed to measure three-dimensional flow, which would be advantageous in boreholes with flow along dipping fractures or in unconsolidated aquifers that have some component of vertical flow near discharge or recharge points. A wireline packer was used successfully in this study with the hydrophysical logging to cut off the vertical flow in two wells, which allowed the natural horizontal flow to re-establish across the well above the packer. Unfortunately, a wireline packer was not available for use with the ADV and colloidal borescope. The wireline packer most likely would not work with the KVA flowmeter because the power cable would interfere with the fuzzy-packer sealing against the borehole wall. Future versions of the ADV and colloidal borescope would benefit from built-in packers above and/or below the sampling zone of the tool when measuring horizontal flow.

The flowmeters are oriented for direction and positioned in the well by various means. The KVA flowmeter is oriented by a magnetic compass attached to the aluminum extension rods above the ground. After the KVA probe is positioned at the desired measurement depth, the aluminum extension rods are rotated manually to align the probe with magnetic north. A second measurement is made after rotating the rods and flowmeter 180 degrees. The combination of the two measurements is used to determine the actual flow direction. The ADV and colloidal borescope are oriented for direction by use of an internal magnetometer (electronic compass). The accuracy and orientation of the magnetometer can be checked through a calibration process. The acquisition software for both systems incorporates the orientation of the magnetometer and magnetic declination to provide flow directions referenced to true north. Hydrophysical logging does not measure flow directions.

The reproducibility of the tool orientation, with respect to azimuth or north, is critical for making repeat measurements with each tool and for making comparisons among the different tools. Because the KVA flowmeter uses a standard magnetic compass and is lowered on fixed rods, the orientation of the probe should not change as the tool is moved to different depths (assuming the compass is read properly and the borehole does not deviate from vertical). Borehole deviation possibly could produce rod twist that might change the orientation of the probe, relative to the compass at land surface. Magnetometers in the ADV and colloidal borescope, if working properly, continuously register the orientation of magnetic north. Magnetic declination should not be a source of error for this study because the two sites have a magnetic declination of 1 degree or less, based on the available topographic maps. The ADV is the only instrument that has a built-in compensator to adjust for pitch from vertical because it measures three-dimensional flow. In boreholes with a severe deviation from vertical, it is possible that the KVA flowmeter and colloidal borescope would no longer measure horizontal flow because their sampling planes would no longer be horizontal.

The KVA flowmeter is positioned vertically by spring-locked aluminum rods with fixed lengths of 5 and 10 ft. The KVA probe is attached to the bottom of the lowest rod, and extensions are added at land surface until the desired depth is reached. The aluminum rods are secured at land surface with a clamp that rests on the casing. The exact length of the rods and therefore the depth of the meter can be measured to the hundredth of a foot. The ADV is positioned vertically, using a cable drawworks with an electronic depth encoder that displays depth to the hundredth of a foot. The colloidal borescope is positioned vertically by manually lowering the probe and cable to the desired depth. Depths are marked on the cable, and the cable is secured at the surface with a wooden clamp. The hydrophysical-logging tool is raised and lowered, using a cable drawworks with an electronic depth encoder that displays depth to the hundredth of a foot. The data-acquisition software records the depths with the conductivity and temperature data.

The reproducibility of the tool positioning, with respect to depth in the borehole, is critical for making repeat measurements with a given tool and for making comparisons among the different tools. Errors in the drawworks or depth encoders could prevent the tools from being positioned exactly at the target depth. Human error in managing the rods with the KVA flowmeter or the cable with the colloidal borescope could prevent the tools from being positioned exactly at the target depth.

The minimum velocity resolution of the methods ranges from stagnant or zero flow to 25.9 ft/d. The KVA flowmeter can measure velocities from 0.1 to 500 ft/d when used with the fuzzy packer. The KVA flowmeter also can measure zero-flow conditions indirectly by recording data that are indeterminate for direction. When a flow vector cannot be resolved, it is usually because velocities are near zero. The ADV has the highest minimum velocity resolution at 25.9 ft/d and the highest upper limit at 691,200 ft/d (8 ft/s). The colloidal borescope can detect stagnant or zero-flow conditions if colloids are visible. The upper limit of velocity measurement with the colloidal borescope, theoretically, is about 7,085 ft/d. The hydrophysical logging can determine velocities down to about 0.01 ft/d, and it can determine a maximum flow rate of about 1,000 gal/min.

The KVA flowmeter, ADV, and colloidal borescope make point measurements. The thermistors on the KVA probe are about 1-inch long and are positioned in about a 1-inch-diameter circle around the heat source. Therefore, the measuring volume for the KVA flowmeter is approximately 1 cubic inch. The measurements can be affected by flow passing through the fuzzy packer, which will include a taller sampling zone at the borehole wall. The field of view for the ADV and colloidal borescope is a thin horizontal plane through the borehole. The measuring volume for the ADV can be adjusted through the acquisition software; it varies from 0.008 to 0.028 cubic inch. The field of view for the colloidal borescope is about 0.039 inch by 0.055 inch by 0.0039 inch (1.0 mm by 1.4 mm by 0.1 mm) (Kearl and others, 1992), which equates to a measuring volume of approximately 8.36 x 10^{-6} cubic inches (0.14 mm^3). The hydrophysical logging makes continuous measurements along the entire borehole; its calculations are based on depth intervals selected for evaluation.

Smaller measured volumes require greater accuracy in vertically positioning the tools in the borehole. For this study, the KVA flowmeter was the first tool to be deployed; depths were measured carefully to the hundredth of a foot with a ruler and the fixed-length rods. It is possible that the other methods did not position the tools to the exact depths measured for the KVA flowmeter because they used cables and different measuring devices.

Data processing could be accomplished on site, to some extent, with all of the tested systems. The KVA flowmeter determined flow direction on site, but the velocities were in machine units that had to be converted with a calibration chamber in the lab. Velocities measured in the borehole with the KVA flowmeter were corrected to seepage velocities in the aquifer, using results from the calibration chamber and available estimates of hydraulic conductivity for the wells. The ADV and colloidal borescope produced on-site determinations of ground-water velocity and direction, which could be refined later. The hydrophysical logging could determine ground-water velocity on site with the computer software, but the majority of the data processing was done off site.

Evaluation and Comparison of the Flowmeter Measurements

In this section, the results of the measurements made with each of the flowmeter methods will be evaluated and compared for each of the test wells. These data are compared for the depths in each test well where measurements were made with at least two of the methods. At depths where multiple measurements were made, only the first measurement is shown in the graphs. The repeat measurements are shown in separate illustrations within the discussions of the data collected with each tool. Velocity values are plotted on a logarithm scale so that the low values, as well as the high values, are visible.

For comparison purposes, the velocities measured in the borehole with the ADV and colloidal borescope have been reduced by a factor of 3 to estimate the seepage velocity in the aquifer. This adjustment to estimate the seepage velocity in the aquifer is based on laboratory results with a laser Doppler velocimeter presented by Momii and others (1993) and is within the range of reduction factors observed by Kearl (1997). The ADV and colloidal borescope make measurements at the center of the open borehole where velocities should be highest. Velocities measured with the ADV and colloidal borescope were not reduced for measurements made at the open fractures in the wells at Fort Campbell. It was assumed that the ground-water velocity in the open fractures would be similar to the velocity in the boreholes. The velocities measured with the KVA flowmeter were adjusted to seepage velocities in the aquifer, using the methods presented in the sections on the KVA flowmeter. All of the velocities determined with the hydrophysical logging were relatively low (table 23) and have not been reduced for the comparisons presented in this section. The hydrophysical logging may have sufficiently accounted for any borehole-magnification effects. Therefore, the velocities shown in figures 83 through 87 are estimates of the seepage velocity in the aquifer, based on the velocities measured in the borehole. The original measurements of velocity in the borehole are listed in data tables in the previous sections covering each flowmeter.

In most instances, the KVA flowmeter reported a lower velocity than the ADV or colloidal borescope. Also, the KVA flowmeter recorded a smaller range of velocities in each well than did the other two methods. The KVA flowmeter measures the velocity of the ground water flowing through the glass beads and fuzzy packer, whereas the other methods measure the velocity through the open borehole. This fundamental difference in the way horizontal velocities are measured may prevent any meaningful comparisons of the horizontal velocities measured in the borehole. Ideally, adjusting the velocities in the borehole to seepage velocities in the aquifer should provide more accurate comparisons; however, the flow-magnification factor of 3 applied to the ADV and colloidal borescope measurements is an assumed value. In many instances, the velocity from the KVA flowmeter was 10, 20, or more times lower than the velocity from the ADV or colloidal bore-

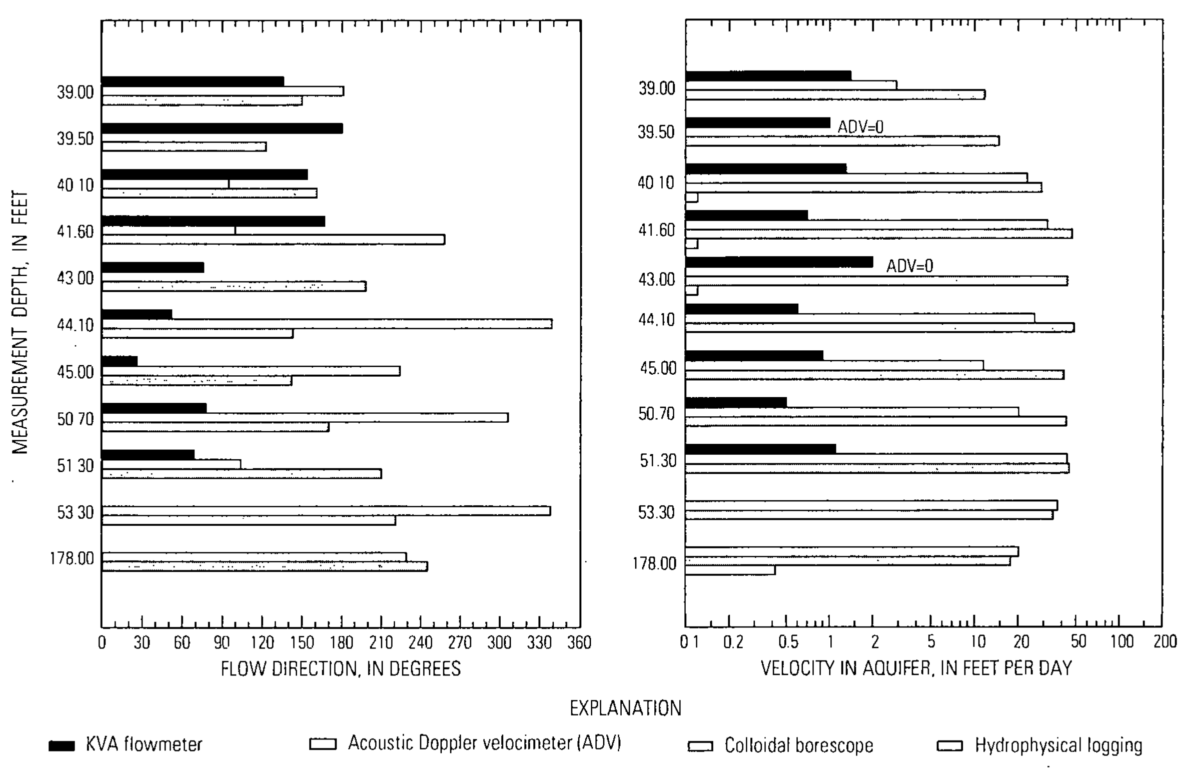


Figure 83. Flow directions and adjusted velocities for measurements made at selected depths in well JPG-5, Jefferson Proving Ground, Indiana.

scope. The hydrophysical logging provided measurements of velocity over an interval rather than at a point. The hydrophysical logging does not determine flow directions. The velocities determined with the hydrophysical logging are included in the comparisons where the intervals coincide with the depths at which point measurements were made with the other methods. The velocities estimated with the hydrophysical logging compare most favorably to the lower velocities measured with the KVA flowmeter.

The actual ground-water velocities and flow directions at the well sites are not known; therefore, the measurements cannot be evaluated for accuracy. If the actual ground-water velocities were known, each of the methods could be evaluated for how the velocities measured in the borehole were affected by the acceleration of the flow field at the borehole. A valuable follow-up study to this work could be an evaluation in laboratory or known field conditions for unconsolidated and bedrock aquifers. Such a study could determine how borehole velocities measured with each of the methods need to be adjusted to provide representative seepage velocities. The natural seepage velocities in the aquifer could be valuable to ground-water and contaminant-transport modelers for site assessment and remediation activities. Lacking such a comprehensive study, the velocities measured in the borehole for this study with the various methods have been adjusted as described above for the purpose of comparison in figures 83 through 87.

Some of the measurements with the colloidal borescope were identified by the contractor as providing reliable flow directions or consistent flow, representing a valid measurement in a preferential-flow zone. This "qualification" implies that all of the other measurements with the colloidal bore-

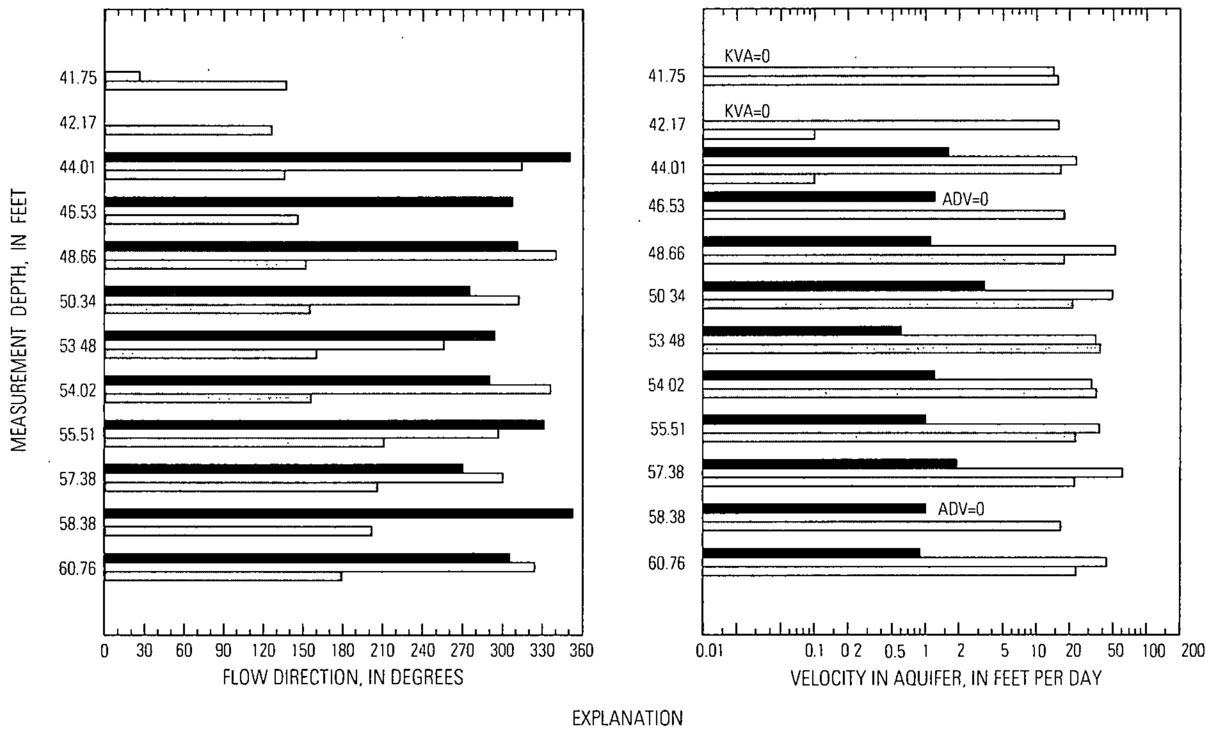


Figure 84. Flow directions and adjusted velocities for measurements made at selected depths in well JPG-2, Jefferson Proving Ground, Indiana.

scope are suspect because the average flow direction probably does not represent the actual flow direction through the well or there may not be horizontal flow through the well. With the KVA flowmeter, an unresolved flow direction implied a zero or near-zero velocity.

In well JPG-5, there were measurements with at least two of the flowmeters at 11 depths (fig. 83). Measurements of velocity were made with each of the four methods at depths of 40.10, 41.60, and 43.00 ft. The KVA flowmeter was not used at depths of 53.30 and 178.00 ft. The ADV measured zero velocity (after being adjusted for background noise, table 9) at depths of 39.50 and 43.00 ft. At most depths in well JPG-5, the flow directions determined by the various flowmeters did not show much agreement. The flow directions were similar for the three tools at a depth of 39.00 ft, where they were 136, 150, and 181 degrees. At 40.10 ft, the KVA flowmeter and colloidal borescope were similar at 154 and 161 degrees. At 178.00 ft, the ADV and colloidal borescope measured similar directions of 229 and 245 degrees. Velocities determined with the hydrophysical logging are shown for the point depths included in the intervals 40 to 44 ft and 160 to 200 ft.

The graphs of flow direction show compass direction in degrees—0 and 360 represent north, and 180 represents south. Flow direction is referenced to magnetic north for the KVA flowmeter and true north for the ADV and colloidal borescope. The difference in magnetic north and true north would not produce a noticeable difference

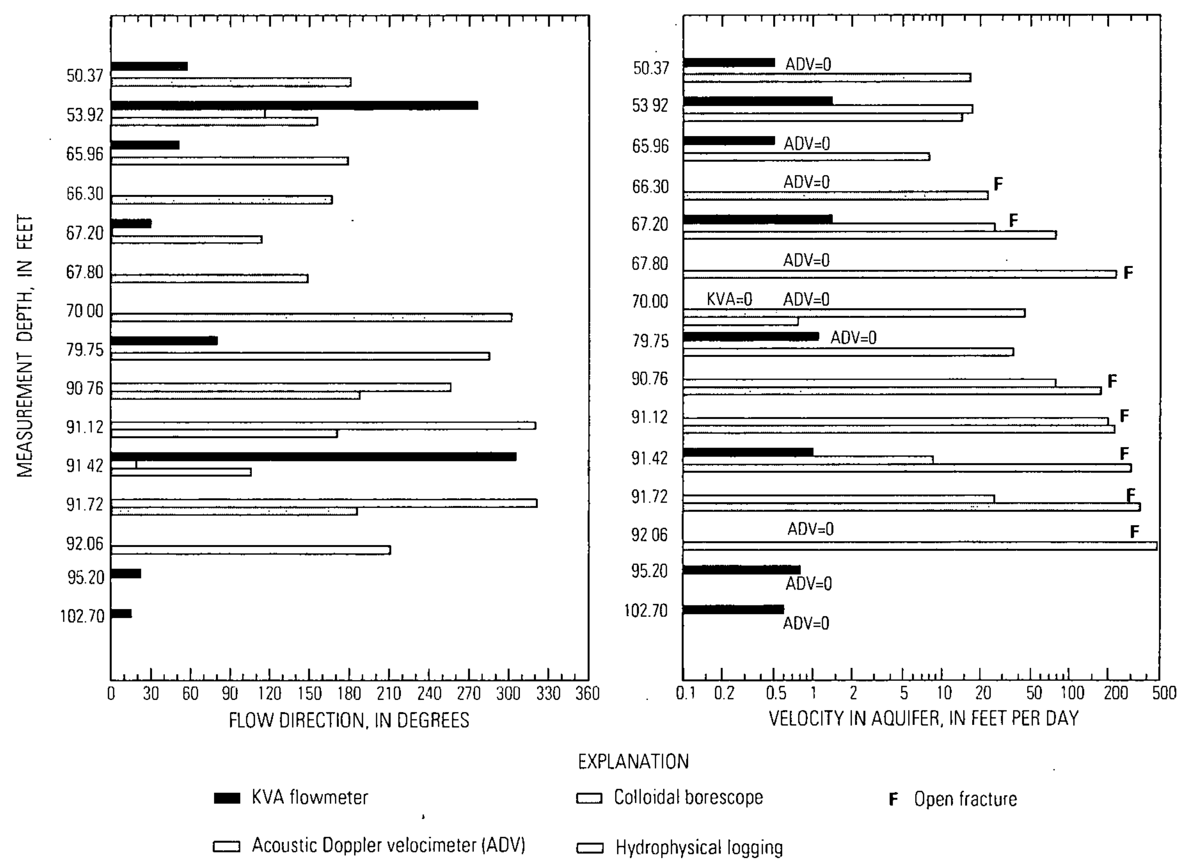


Figure 85. Flow directions and adjusted velocities for measurements made at selected depths in well FC-29, Fort Campbell, Kentucky.

in flow direction because a magnetic declination of about 1 degree was applied to the ADV and colloidal-borescope systems at both study sites. Changes in magnetic declination over time not accounted for in this study also would be insignificant for the purpose of comparing flow directions in this section. Magnetic declinations were obtained from topographic maps of various dates for the study sites.

Data for well JPG-5 show that the velocities determined with the KVA flowmeter do not compare with those determined with the ADV and colloidal borescope. Except for the two depths where the ADV velocity was zero, the KVA flowmeter measured consistently lower velocities that ranged from 0.5 to 2.0 ft/d. The hydrophysical logging estimated a velocity of 0.12 ft/d for the interval of 40 to 44 ft and 0.42 ft/d for the interval 160 to 200 ft. Velocities measured with the ADV ranged from 0 to 43.3 ft/d and velocities measured with the colloidal borescope ranged from 11.7 to 48.7 ft/d. At most depths, the ADV and colloidal borescope measured similar velocities.

In well JPG-2, there were measurements with at least two of the flowmeters at 12 depths under ambient flow conditions (fig. 84). Measurements of velocity were made with each of the four methods at a depth of 44.01 ft. The KVA flowmeter measurements at 41.75 and 42.17 ft were indeterminate, implying a zero or near-zero velocity. A measurement was not made with the ADV at a depth of 42.17 ft. The ADV measured zero velocity (after being adjusted for background noise, table 10) at depths of 46.53 and 58.38 ft.

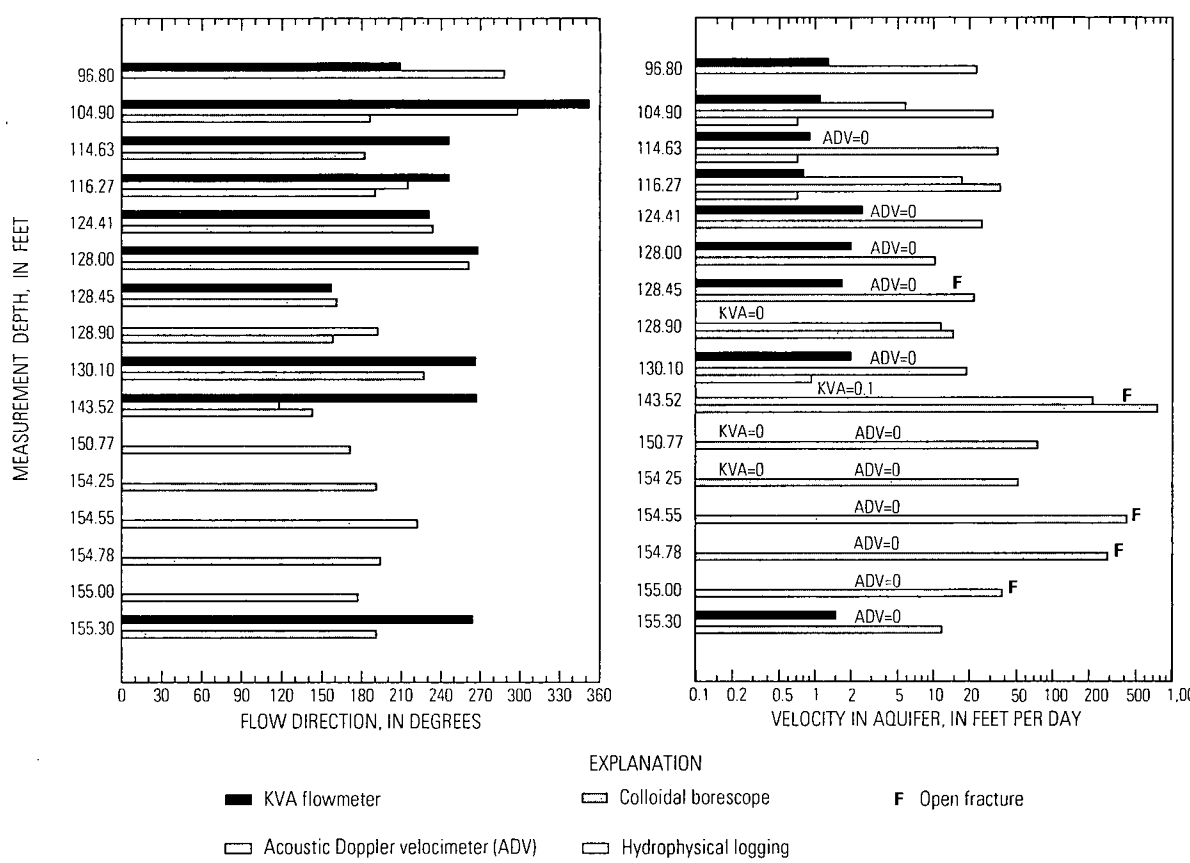


Figure 86. Flow directions and adjusted velocities for measurements made at selected depths in well FC-15, Fort Campbell, Tennessee.

At most depths in well JPG-2, the flow directions did not show much agreement among the three flowmeters. The KVA flowmeter consistently measured flow directions of west to north, ranging from 270 degrees to 353 degrees. The ADV also had 8 of 11 measurements that recorded flow directions to the west and northwest, ranging from 283 to 340 degrees. The colloidal borescope did not record similar flow directions for the depths listed in figure 84. The colloidal borescope measurements recorded flow directions of southeast to southwest, ranging from 126 to 211 degrees.

Data for well JPG-2 show that velocities determined with the KVA flowmeter do not agree closely with those determined with the ADV and the colloidal borescope. Except for the two depths where the ADV velocity was zero, the KVA flowmeter measured consistently lower velocities that ranged from 0 to 3.4 ft/d. Velocities measured with the ADV ranged from 0 to 60.3 ft/d, and velocities measured with the colloidal borescope ranged from 15.7 to 38.0 ft/d. The hydrophysical logging estimated a velocity of 0.1 ft/d for the depth interval of 42 to 46 ft. At several depths, the ADV and colloidal-borescope velocities agreed.

Measurements made in well JPG-2 while pumping nearby well JPG-1 were made at several depths but at various elapsed times of pumping. The water-level plots for the wells indicate that the aquifer responded consistently for the four pumping tests. It did not seem reasonable, however, to compare measurements with several hours difference in elapsed pumping time; therefore, the measurements made during the pumping tests are not compared in this section.

Measurements were made at 15 depths in well FC-29 with at least two of the flowmeters, and at 7 depths with each of the directional tools (fig. 85). The KVA flowmeter measurement at

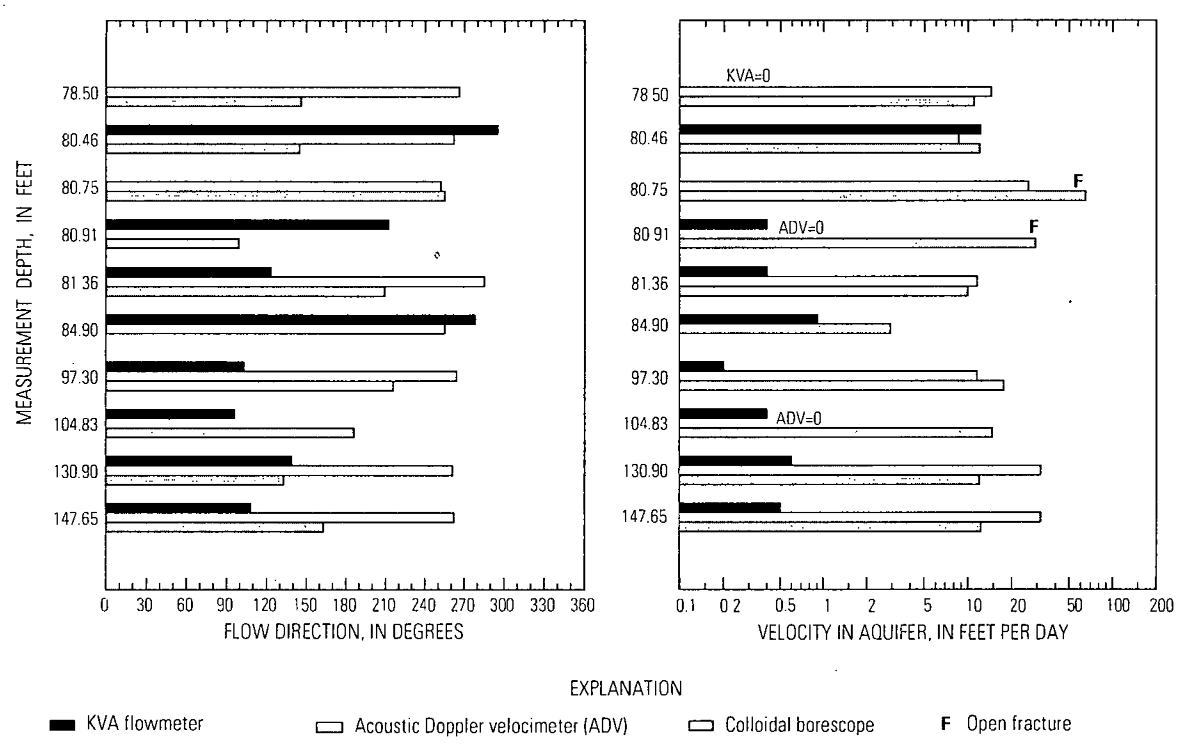


Figure 87. Flow directions and adjusted velocities for measurements made at selected depths in well FC-16, Fort Campbell, Kentucky.

70.00 ft was indeterminate for direction and velocity, which implies a zero or near-zero velocity. The hydrophysical logging estimated a velocity of 0.77 ft/d over the depth interval 68 to 78 ft while using a wireline packer set at a depth of 89 ft (this velocity is plotted at 70.00 ft in fig. 85). The ADV measured zero velocity (after being adjusted for background noise, table 13) at depths of 50.37, 65.96, 66.30, 67.80, 70.00, 79.75, 92.06, 95.20, and 102.70 ft. Velocities measured with the ADV and colloidal borescope at the open fractures were not adjusted for the flow-magnification factor. The open fractures in well FC-29 were at depths of 66.16 through 68.06 ft and 90.76 through 92.06 ft.

Many of the measurements in well FC-29 possibly were affected by the downward vertical flow between the two open fractures. None of the measured flow directions appear to agree with each other. The KVA flowmeter measured low velocities relative to the ADV and colloidal borescope, ranging from 0 to 1.4 ft/d. The velocities measured with the ADV range from 0 to 199 ft/d, and the velocities measured with the colloidal borescope range from 8.0 to 482 ft/d. Only at two depths, 53.92 and 91.12 ft, did the ADV and the colloidal borescope measure similar velocities. The KVA flowmeter may have measured artificially reduced velocities at the open fractures (67.2 and 91.42 ft) because of flow bypassing the fuzzy packer.

Measurements were made at 16 depths in well FC-15 with at least two of the flowmeters, and at 11 depths with each of the three directional tools (fig. 86). The KVA flowmeter measurements at 128.90, 150.77, and 154.25 ft were indeterminate for direction and velocity, which implies a zero or near-zero velocity. The ADV measured zero velocity (after being adjusted for background noise, table 14) at 11 of the 16 measured depths. Velocities measured with the ADV and colloidal borescope at the open fractures were not adjusted for the flow-magnification factor. The open fractures in well FC-15 were at depths 128.20 through 128.70 ft, 143.38 through 143.65 ft, and 154.55 through 155.00 ft.

As in well FC-29, many of the measurements in well FC-15 possibly were affected by the vertical flow between the open fractures. Most of the measured flow velocities and directions in well FC-15 do not agree. At three depths—124.41, 128.00, and 128.45 ft—the KVA flowmeter and colloidal borescope measured flow directions within a few degrees of each other. The measurement at 128.00 ft was just above the upper fracture, and the measurement at 128.45 was at the middle of the upper fracture. Only one measurement, at 128.90 ft, had comparable velocities for the ADV and colloidal borescope. The velocities measured with the KVA flowmeter ranged from 0 to 2.5 ft/d. The KVA measurements at the open fractures (128.45 and 143.52 ft) may have been affected by flow bypassing the fuzzy packer. The velocity at 143.52 ft with the KVA flowmeter is 0.1 ft/d. The velocities measured with the ADV ranged from 0 to 216 ft/d, and the velocities measured with the colloidal borescope ranged from 10.3 to 759 ft/d.

The hydrophysical logging used a wireline packer in well FC-15 to shut off the vertical flow in the borehole. A velocity of 0.71 ft/d was estimated for the depth interval 102 to 119 ft, and a velocity of 0.93 ft/d was estimated for the depth interval 130 to 137 ft. These velocities are similar to those measured with the KVA flowmeter at these depths.

Measurements were made at 10 depths in well FC-16 with at least two of the flowmeters and at 8 depths with each of the three directional tools (fig. 87). Hydrophysical logging was not done in well FC-16 for estimating horizontal flow. The KVA flowmeter measurement at 78.50 ft was indeterminate for direction and velocity. The ADV measured zero velocity (after being adjusted for background noise, table 15) at depths of 80.91 and 104.83 ft. The KVA flowmeter was not used at 80.75 ft, and the colloidal borescope was not used at 84.90 ft. Velocities measured with the ADV and colloidal borescope at the open fracture were not adjusted for the flow-magnification factor. The open fracture in well FC-16 was at 80.75 through 81.06 ft.

At none of the depths shown in figure 87 did all three of the tools measure flow directions that agreed. At a depth of 80.75 ft, within the open fracture, the ADV and colloidal borescope measured essentially the same flow direction. At 84.90 ft, the KVA flowmeter measured a flow direction of 278 degrees, compared to 255 degrees for the ADV. At 130.90 ft, the KVA flowmeter measured 139 degrees, compared to 133 degrees for the colloidal borescope.

At one depth, 80.46 ft, the three tools measured comparable velocities. The KVA flowmeter measured 12.2 ft/d, the ADV measured 8.6 ft/d, and the colloidal borescope measured 12.0 ft/d. All other velocities with the KVA flowmeter were less than 1.0 ft/d. The velocities measured with the KVA flowmeter ranged from 0 to 12.2 ft/d. The velocities measured with the ADV ranged from 0 to 31.7 ft/d, and the velocities measured with the colloidal borescope ranged from 10.0 to 65.0 ft/d. The ADV and colloidal borescope measured similar velocities at depths of 78.50, 81.36, and 97.30 ft.

The KVA flowmeter consistently yielded horizontal-flow magnitudes considerably less than those provided by the acoustic Doppler velocimeter and colloidal borescope. This difference was expected because the design of the KVA flowmeter at least partially 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 KVA flowmeter, presumably because the hydrophysical logging also effectively compensated for the effect of the borehole on the flow field and because velocities were averaged over a length of borehole rather than at a point. The acoustic Doppler velocimeter and colloidal borescope have discrete sampling points at the center of the borehole; they are capable of measuring preferential-flow velocities that can be substantially higher than the average velocity through a length of borehole.

It is uncertain which technique provided the most accurate measurements of flow in the borehole and which measurements were most representative of the flow in the aquifer. Additional research is needed to determine how the borehole-flow measurements relate to flow in fractured bedrock aquifers. The flowmeters may need to be evaluated under controlled laboratory conditions to determine which 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 bedrock aquifers and unconsolidated aquifers, and directional differences in individual wells for hydraulically separated flow zones.

All of the flowmeter methods can obtain measurements of horizontal flow. Perhaps future research can determine how velocities measured with each method relate to the natural seepage velocities in aquifers for different conditions, such as well diameter, type of aquifer, and width of fractures.

Summary and Conclusions

Three borehole flowmeters that measure the direction and magnitude of horizontal flow and hydrophysical logging that measures the magnitude of horizontal flow 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 in August and September 1999. The three horizontal flowmeters made point measurements of flow velocity and direction, and the hydrophysical logging provided average discharge and velocity through the borehole for selected depth intervals. The flowmeters independently measured flow in zones that background geophysical logging and vertical-flow logging had identified as water producing or where geologic features indicated favorable conditions for measuring horizontal flow.

The three flowmeters evaluated are the KVA horizontal heat-pulse flowmeter, the acoustic Doppler velocimeter, and the colloidal borescope. Each of these flowmeters uses a different technology to measure ground-water velocity and flow direction. The KVA flowmeter measures the rate of convection of a parcel of heated water; the acoustic Doppler velocimeter measures acoustic reflection from particles in the water; and the colloidal borescope uses video particle tracking. Hydrophysical logging involves replacement of the borehole fluid with deionized water, followed by a series of fluid-electrical-conductivity logs used to measure the locations and compute the rates at which ground water enters the borehole.

Ten to 12 measurements were made each day with the KVA flowmeter; each measurement took 30 to 45 minutes to complete. The design and principles of operation require the fuzzy packer surrounding the thermal sensors to fit snugly against the borehole wall to create a hydraulic connection between the formation and fuzzy packer. The KVA flowmeter will not work effectively in open fractures where the borehole diameter is larger than the fuzzy packer. Measurements with the KVA flowmeter also can be affected by vertical flow in the borehole if the fuzzy packer is not seated against the borehole wall.

The acoustic Doppler velocimeter was the only flowmeter designed to measure three-dimensional flow. The acoustic Doppler velocimeter consistently measured downward vertical velocities in the test wells. The downward vertical velocity was attributed to particles falling through the water column after being scraped from the borehole wall. A baffle/skirt system was used to help suppress the vertical flow and isolate the horizontal flow. The effectiveness of the baffle to stop vertical flow is unknown, however. Measurements inside the casing indicated that the ADV was affected by apparent background noise. The apparent background noise for horizontal velocity was subtracted from each measurement in each well. Approximately 25 measurements were made in each well; each measurement took about 10 to 15 minutes. The data-acquisition software allows for continuous graphing of velocity and direction, making it evident when conditions are appropriate to collect data and if the velocimeter is positioned at a depth where the velocity and direction are consistent.

Data for most of the colloidal borescope measurements indicated "swirling" flow, characteristic of low- or no-flow zones where there is no continuous hydraulic connection between the well and the surrounding formation. In zones with swirling flow, it is not possible to obtain a reliable measurement of ground-water velocity and flow direction. The data are useful, however, for indicating zones of low permeability relative to adjacent preferential flow zones. A rubber disc was attached to the colloidal borescope to act as a baffle to help isolate horizontal flow from vertical flow in the boreholes; however, the effectiveness of this baffle is unknown.

The data-acquisition software allows for continuous graphing of velocity and direction, making it evident if the borescope is positioned at a depth where the velocity and direction are consistent. At such depths, the time span of data collection usually was extended to acquire numerous measurements over 1 to 2 hours. At depths with apparent swirling flow, the data collection usually was stopped after about 15 minutes, and the tool was moved to the next position to be tested. About 18 measurements were made in each test well with the colloidal borescope. Natural colloids need to be present in the water column for the borescope to work; this was not a problem in the test wells.

The hydrophysical logging provided estimates of flow rate and velocity over specific depth ranges in each well. Each hydrophysical logging measurement required 1 day. Some wells were logged under two conditions. At Jefferson Proving Ground, one well was logged under ambient conditions and again while a nearby well was pumped. At Fort Campbell, two wells were logged under open-hole conditions and again after a wireline packer had been used to shut off the vertical flow in the well. A wireline packer was used to shut off the vertical flow, allowing the natural horizontal flow to be established in the borehole above the packer. The hydrophysical logging was used to measure the horizontal-flow rates and velocities above the packer. Under the open-hole conditions without the packer, the hydrophysical logging measured the vertical-flow rate within the borehole.

Repeat measurements occasionally were made with each of the point-measurement tools. In some instances the measurements repeated the flow direction or velocity; none of the tools consistently provided repeatable measurements of velocity and direction. It is uncertain whether these measurements indicate that none of the methods can provide reliable duplicate measurements of velocity and direction or if the borehole environment in bedrock is not conducive to measuring consistent velocities and directions. In some instances, the original and repeat measurements were made on different days; this could explain some of the variability because hydraulic conditions could change over a 12- to 24-hour period.

At Jefferson Proving Ground, measurements were made in one of the wells with each method while a nearby well was pumped to induce horizontal flow to the pumped well. Drawdown in the measured well indicated that the two wells were hydraulically connected. None of the directional flowmeters recorded a change in flow direction completely towards the pumped well, suggesting that the hydraulic connection was more complicated than simple radial flow through bedding-plane porosity. The colloidal-borescope measurements did show that the overall trend of flow directions was more towards the pumping well than the trend during ambient conditions. On average, the KVA flowmeter and acoustic Doppler velocimeter showed a slight increase in velocity during the pumping, and the colloidal borescope showed a decrease in velocity during pumping. The hydrophysical logging showed an increase in velocity during pumping for the three test intervals evaluated. Two of the intervals evaluated with the hydrophysical logging were in the deeper part of the well, where point measurements were not made with the KVA flowmeter or the acoustic Doppler velocimeter.

Overall, the measurements did not show the anticipated effect of increased velocities and flow directions towards the pumping well. The pumping time was probably insufficient to cause a consistent increase in velocity and to cause a complete change in flow direction towards the pumping well. Even though the two wells were connected hydraulically, it is possible that some of the tested zones were not.

Velocities and flow directions were compared for each depth in the test wells where measurements were made with at least two of the flowmeters. Because the KVA flowmeter measures flow through a controlled environment (fuzzy packer filled with glass beads), the velocities may not be comparable to the other two tools. The acoustic Doppler velocimeter and the colloidal borescope measure flow at the center of the open borehole, if the tools are positioned in the center of the borehole. To compensate for the different methods, the velocities measured in the borehole were adjusted to estimates of the seepage velocity in the aquifer. The KVA flowmeter has a correction procedure for estimating the seepage velocity in the aquifer. This correction procedure uses results from a calibration chamber and estimates of field hydraulic conductivities to compute a ratio that approximates the flow-magnification factor of the borehole. Velocities for the acoustic Doppler velocimeter and the colloidal borescope were adjusted by reducing the velocities measured in the borehole by a theoretical flow-magnification factor of 3. The theoretical flow-magnification factor of 3 is based on the analytical solution for flow across a cylindrical, water-filled borehole embedded in a homogeneous medium.

A comparison of the measurements made in each well indicated that the three point-measurement flowmeters rarely measured similar velocities and flow directions; at several depths, two of the methods provided similar flow directions or velocities but usually not both. The KVA flowmeter consistently measured lower velocities than the other two methods. In many instances, the velocity measured with the KVA flowmeter was 10, 20, or more times lower than those recorded by the other two tools. The velocities estimated with the hydrophysical logging were typically very low and were most comparable to the velocities measured with the KVA flowmeter. At many depths, the acoustic Doppler velocimeter and colloidal borescope measured similar velocities; however, the two tools seldom measured a similar flow direction. The KVA flowmeter and the hydrophysical logging apparently compensate for the acceleration of the flow field in the borehole. The acoustic Doppler velocimeter and colloidal borescope have discrete measuring points at the center of the borehole where the velocities should be greatest. Some of the variability in the measurements most likely can be attributed to naturally occurring changes in hydraulic conditions during the 1-month study period.

Complications related to vertical flow in the boreholes highlight the importance of using background logging or screening 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 the actual velocities and flow directions were unknown, it is uncertain which technique provided the most accurate measurements of flow in the borehole and which measurements were most representative of the flow in the aquifer. The KVA flowmeter measured lower velocities than the acoustic Doppler velocimeter or the colloidal borescope. It is uncertain whether the fuzzy packer tends to restrict the horizontal flow through the well, or whether it improves the measuring environment by reducing vertical disturbances to the water column. The velocity data based on the hydrophysical logging compare better with the lower velocities of the KVA flowmeter than with those of the other two methods. Additional research is needed to determine how the borehole-flow measurements 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 bedrock aquifers and unconsolidated aquifers, and directional differences in individual wells for hydraulically separated flow zones.

References Cited

AquaVision Environmental LLC, 2000, AquaVision Environmental LLC. From URL http://www.aquavisionenv.com/ accessed June 30, 2000, HTML format.

Bidaux, Pascal, and Tsang, C.F., 1991, Fluid flow patterns around a well bore or an underground drift with complex skin effects: Water Resources Research, v. 27, no. 11, p. 2,993–3,008.

Cohen, A.J.B., 1995, Hydrogeologic characterization of fractured rock formations—A guide for groundwater remediators: Earth Sciences Division, Ernest Orlando Lawrence Berkeley National Laboratory, University of California, Berkeley, Calif., Prepared for USDOE under contract number DE-AC03-76SF0098, LBL-38142/UC-800, 144 p.

Crowder, Robert, Paillet, Frederick, and Hess, Alfred, 1994, High resolution flowmeter logging—A unique combination of borehole geophysics and hydraulics; Part I, Flowmeter techniques and equipment development, *in* Proceedings of the Symposium on the Application of Geophysics to Engineering and Environmental Problems, March 27–31, 1994: Environmental and Engineering Geophysical Society, Boston, Mass., p. 361–379.

Department of Energy-Oak Ridge National Laboratory, 1993, Technology information profile (rev. 2) for ProTech, technology name—Colloidal borescope: DOE ProTech Database, TTP Reference Number OR-11211-04, July 15, 1993.

Drost, Walter, Klotz, Dietmar, Koch, Arnd, Moser, Heribert, Neumaier, Ferdinand, and Rauert, Werner, 1968, Point dilution methods of investigating groundwater flow by means of radioisotopes: Water Resources Research, v. 4, no. 1, p. 125–146.

Evans, D.G., Lane, C.B., Paillet, Frederick, and Pedler, W.H., 1996, Hydraulic characterization of fractures in the piedmont of North Carolina using fluid conductivity and transient flow logging: 1996 GSA Abstracts with Programs, Southeastern Section, p. 11.

Freeze, R.A., and Cherry, J.A., 1979, Groundwater: Prentice-Hall, Inc., Englewood Cliffs, N.J., 604 p.

Gray, H.H., 1972, Geologic map of the 1° x 2° Louisville quadrangle, Indiana, showing bedrock and unconsolidated deposits: Indiana Department of Natural Resources, Geological Survey, Regional Geologic Map No. 6.

Greeman, T.K., 1981, Lineaments and fracture traces, Jennings County and Jefferson Proving Ground, Indiana: U.S. Geological Survey Open-File Report 81-1120, 17 p.

Guthrie, Marilyn, 1986, Use of a Geo Flowmeter for the determination of ground water flow direction: Ground Water Monitoring Review, v. 6, no. 2, p. 81–86.

Hale, F.V., and Tsang, C.F., 1988, A code to compute borehole fluid conductivity profiles with multiple feed points: LBL-24928, Lawrence Berkeley Laboratory, University of California, Berkeley, Calif.

Hanson, R.T., and Nishikawa, Tracy, 1996, Combined use of flowmeter and time-drawdown data to estimate hydraulic conductivities in layered aquifer systems: Ground Water, v. 34, no. 1, p. 84–94.

Hearst, J.R., Nelson, P.H., and Paillet, F.L., 2000, Well logging for physical properties (2d ed.): John Wiley & Sons, Inc., Chichester, England, 483 p.

Hess, A.E., 1986, Identifying hydraulically conductive fractures with a slow-velocity borehole flowmeter: Canadian Geotechnical Journal, v. 23, no. 1, p. 69–78.

Hill, A.D., 1990, Production logging-theoretical and interpretive elements: Richardson, Tex., Society of Petroleum Engineers Monograph, v. 14, 154 p.

Kabala, Z.J., 1994, Measuring distributions of hydraulic conductivity and specific storativity by the double flowmeter test: Water Resources Research, v. 30, no. 3, p. 685–690.

Kearl, P.M., 1997, Observations of particle movement in a monitoring well using the colloidal borescope: Journal of Hydrology, v. 200, p. 323–344.

Kearl, P.M., and Case, C.M., 1992, Direct field measurement of groundwater velocities: Interdisciplinary Approaches in Hydrology and Hydrogeology, American Institute of Hydrology, p. 91–102.

Kearl, P.M., Korte, N.E., and Cronk, T.A., 1992, Suggested modifications to ground water sampling procedures based on observations from the colloidal borescope: Ground Water Monitoring Review, v. 12, no. 2, p. 155–160.

Kearl, P.M., Korte, N.E., Stites, Mike, and Baker, Joe, 1994, Field comparison of micropurging vs. traditional ground water sampling: Ground Water Monitoring and Remediation, v. 14, no. 4, p. 183–190.

Kearl, P.M., and Roemer, Kirk, 1998, Evaluation of groundwater flow directions in a heterogeneous aquifer using the colloidal borescope: Advances in Environmental Research, v. 2, no. 1, p. 12–23.

Kearl, P.M., Roemer, Kirk, Rogoff, E.B., and Renn, R.M., 1999, Characterization of a fractured aquifer using the colloidal borescope: Advances in Environmental Research, v. 3, no. 1, p. 49–57.

References Cited—Continued

Kentucky Geological Survey, 2000, Physiographic map of Kentucky: From URL http://www.uky.edu/KGS/ accessed March 10, 2000, HTML format.

Kerfoot, W.B., 1982, Comparison of 2-D and 3-D ground-water flowmeter probes in fully-penetrating monitoring wells *in* Proceedings, The Second National Symposium on Aquifer Restoration and Ground Water Monitoring: Water Well Journal Publishing Co., Worthington, Ohio, p. 264–268.

———1988, Monitoring well construction, and recommended procedures for direct ground-water flow measurements using a heat-pulsing flowmeter, *in* Ground water contamination—Field methods: ASTM Special Technical Publication 963, American Society for Testing and Materials, Philadelphia, Penn., p. 146–161.

———1992, The use of borehole flowmeters and slow-release dyes to determine bedrock flow for well-head protection, *in* Proceedings, The Sixth National Outdoor Action Conference on Aquifer Restoration, Ground Water Monitoring, and Geophysical Methods, National Ground Water Association, May 11–13, 1992, Las Vegas, Nev.: p. 755–763.

———1995, Independent verification of heat pulse groundwater flowmeter results through long term observation and tracer tests on Superfund sites, *in* Hydrocarbon Contaminated Soils: v. V, Amherst Scientific Publishers, Amherst, Mass., p. 37–49.

Kerfoot, W.B., Beaulieu, Giselle, and Kiely, Lawrence, 1991, Direct-reading borehole flowmeter results in field applications, *in* Proceedings, The Fifth National Outdoor Action Conference on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods, National Ground Water Association, May 13-16, 1991, Las Vegas, Nev.: p. 1,073–1,084.

Keys, W.S., 1990, Borehole geophysics applied to ground-water investigations: Techniques of Water-Resources Investigations of the U.S. Geological Survey, book 2, chap. E2, 150 p.

Klemic, Harry, 1966, Geologic map of the Herndon quadrangle, Kentucky-Tennessee: U.S. Geological Survey Geologic Quadrangle Map GQ-572, scale 1:24,000, 1 sheet.

Korte, Nic, Kearl, P.M., Siegrist, R.L., Muck, M.T., and Schlosser, R.M., 2000, An evaluation of horizontal recirculation using single-well tests, pumping tests, tracer tests, and the colloidal borescope: Ground Water Monitoring Review, v. 20, no. 1, p. 78–85.

Kraus, N.C., Lohrmann, Atle, and Cabrera, Ramon, 1994, New acoustic meter for measuring 3D laboratory flows: Journal of Hydraulic Engineering, v. 120, no. 3, p. 406–412.

Loew, Simon, Tsang, C.F., Hale, Frank, and Hufschmied, Peter, 1991, The application of moment methods to the analysis of fluid electrical conductivity logs in boreholes: LBL-28809, Lawrence Berkeley Laboratory, University of California, Berkeley, Calif., and NDC-8, NAGRA-DOE Cooperative Project, Nagra, Baden, Switzerland.

Miller, R.A., 1974, The geologic history of Tennessee: Tennessee Division of Geology Bulletin 74, 63 p.

Molz, F.J., Morin, R.H., Hess, A.E., Melville, J.G., and Guven, Oktay, 1989, The impeller meter for measuring aquifer permeability variations—Evaluation and comparison with other tests: Water Resources Research, v. 25, no. 7, p. 1,677–1,683.

Molz, F.J., Bowman, G.K., Young, S.C., and Waldrop, W.R., 1994, Borehole flowmeters—Field application and data analysis: Journal of Hydrology, v. 163, p. 347–371.

Molz, F.J., and Young, S.C., 1993, Development and application of borehole flowmeters for environmental assessment: The Log Analyst, v. 34, no. 1, p. 13–23.

Momii, Kazuro, Jinno, Kenji, and Hirano, Fumiaki, 1993, Laboratory studies on a new laser Doppler velocimeter system for horizontal groundwater velocity measurements in a borehole: Water Resources Research, v. 29, no. 2, p. 283–291.

Newhouse, M.W., and Hanson, R.T., 2000, Application of three-dimensional borehole flow measurements to the analysis of seawater intrusion and barrier injection systems, Los Angeles, California, *in* International Symposium on Borehole Geophysics for Minerals, Geotechnical, and Groundwater Applications, 7th, Denver, Colo., 2000, Proceedings: Houston, Tex., The Minerals and Geotechnical Logging Society, A Chapter at Large of the Society of Professional Well Log Analysts, p. 281–292.

Paillet, F.L, 1998, Flow modeling and permeability estimation using borehole flow logs in heterogeneous fractured formations: Water Resources Research, v. 34, no. 5, p. 997–1,010.

———2000, A field technique for estimating aquifer parameters using flow log data: Ground Water, v. 38, no. 4, p. 510–521.

References Cited—Continued

Paillet, Frederick, Crowder, Robert, and Hess, Alfred, 1994, High resolution flowmeter logging—A unique combination of borehole geophysics and hydraulics; Part II, Borehole applications with the heat-pulse flowmeter, *in* Proceedings of the Symposium on the Application of Geophysics to Engineering and Environmental Problems, March 27–31, 1994: Environmental and Engineering Geophysical Society, Boston, Mass., p. 381–404.

Paillet, F.L., Hess, A.E., and Williams, J.H., 1998, Design, operation, and data analysis for a wireline packer system in open boreholes, with field-test results from Belvidere, Illinois: U.S. Geological Survey Open-File Report 98-413, 23 p.

Paillet, F.L., and Pedler, W.H., 1996, Integrated borehole logging methods for wellhead protection applications: Engineering Geology, 42, p. 155–165.

Pedler, W.H., Crowder, R.E., Seracuse, J.M., Myers, N.J., Daniel, James, and Haines, Laurie, 1995, Vertical profiling of aquifer flow characteristics and water quality parameters using hydrophysical logging™, *in* Proceedings of the Symposium on the Application of Geophysics to Engineering and Environmental Problems, April 23–26, 1995, Environmental and Engineering Geophysical Society, Orlando, Fla.: p. 311–318.

Pedler, W.H., Head, C.L., and Williams, L.L., 1992, Hydrophysical logging—A new wellbore technology for hydrogeologic and contaminant characterization of aquifers, *in* Proceedings, The Sixth National Outdoor Action Conference on Aquifer Restoration, Ground Water Monitoring, and Geophysical Methods, National Ground Water Association, May 11–13, 1992, Las Vegas, Nev.: p. 701–715.

Pedler, W.H., and Urish, D.W., 1988, Detection and characterization of hydraulically conductive fractures in a borehole—The emplacement method: EOS, Transactions of the American Geophysical Union, v. 69, no. 44, p. 1,186.

Schimschal, Ulrich, 1981, Flowmeter analysis at Raft River, Idaho: Ground Water, v. 19, no. 1, p. 93–97.

Schneider, A.F., 1966, Physiography, *in* Lindsey, A.A., ed., Natural features of Indiana: Indianapolis, Indiana Academy of Science, p. 40–56.

Shapiro, A.M., Hsieh, P.A., and Haeni, F.P., 1999, Integrating multidisciplinary investigations in the characterization of fractured rock, *in* Subsurface contamination from point sources—Research in characterizing fractured rock aquifers, Proceedings of the Technical Meeting, Charlestown, S.C., May 8–12, 1999: U.S. Geological Survey Toxic Substances Hydrology Program, v. 3/3, section G, 188 p.

Shaver, R.H., Ault, C.H., Burger, A.M., Carr, D.D., Droste, J.B., Eggert, D.L., Gray, H.H., Harper, Denver, Hasenmueller, N.R., Hasenmueller, W.A., Horowitz, A.S., Hutchison, H.C., Keith, B.D., Keller, S.J., Patton, J.B., Rexroad, C.B., and Wier, C.E., 1986, Compendium of Paleozoic rock-unit stratigraphy in Indiana—A revision: Indiana Department of Natural Resources, Geological Survey Bulletin 59, 203 p.

SonTek, Inc., 1996, Modified ADV for 3D velocity measurements in boreholes—Final project report: U.S. Geological Survey Contract Number 1434-95-C-40232, 29 p.

Tsang, C.F., Hufschmied, Peter, and Hale, F.V., 1990, Determination of fracture inflow parameters with a borehole fluid conductivity logging method: Water Resources Research, v. 26, no. 4, p. 561–578.

U.S. Army, 2000, 101st Airborne Division (Air Assault) and Fort Campbell, Ky.: From URL http://www.campbell.army.mil/ accessed February 10, 2000, HTML format.

U.S. Army Test and Evaluation Command, 2000, U.S. Army Test and Evaluation Command Site for the Jefferson Proving Ground: From URL http://www.jpg.apg.army.mil/ accessed February 8, 2000, HTML format.

Vernon, J.H., Paillet, F.L., Pedler, W.H., and Griswold, W.J., 1993, Application of borehole geophysics in defining the wellhead protection area for a fractured crystalline bedrock aquifer: The Log Analyst, January–February 1993, p. 41–56.

Wheatcraft, S.W., and Winterberg, Friedwardt, 1985, Steady state flow passing through a cylinder of permeability different from the surrounding medium: Water Resources Research, v. 21, no. 12, p. 1,923–1,929.

Wilson, C.W., Jr., 1986, Geologic map of the Woodlawn quadrangle, Tennessee: Tennessee Division of Geology, Geological Map GM 300-SE, scale 1:24,000, 1 sheet.

Young, S.C., Pearson, H.S., Moore, G.K., and Clapp, R.B., 1991, Application of the electromagnetic borehole flowmeter technique at the Oak Ridge Laboratory: Tennessee Valley Authority, Report WR28-1-900-247, Norris, Tenn.