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Preliminary Delineation of Contaminated Water-Bearing Fractures Intersected by Open-Hole Bedrock Wells

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Abstract

Contaminated water-bearing fractures intersected by open-hole bedrock wells were preliminarily delineated through a combination of geophysical logging, vertical-flow measurements, and downhole water sampling as part of remedial site investigations in southeastern New York. The wells investigated range from 100 to 450 feet in depth, have only shallow surface casing, and intersect multiple water-bearing zones. The distribution of water-bearing zones that intersect the wells was determined from single-point resistance, caliper, fluid-resistivity, temperature, and acoustic-televiewer logs. Measurable flow in the wells was downward from upper producing zones to lower receiving zones that are poorly connected in the aquifer and that differ in hydraulic head as a result of nearby pumping. A downhole sampler was used to collect discrete and composite water samples for analysis of volatile organic compounds from producing zones that are self-purging as a result of flow in the wells.

The results obtained at two of the study sites are presented — the Spring Valley wellfield and the Mahopac business district. At the Spring Valley wellfield, a supply well completed in Mesozoic sandstone and conglomerate intersects water-bearing zones at depths of 204 to 245 feet that produced contaminated water that was received by a zone at 278 feet. In the same well, a deeper zone at 345 feet produced uncontaminated water that was received by a zone at 403 feet. Correlation of information from the well, geophysical logs and drill cores from nearby monitoring wells, and bedrock outcrops indicates that most of the water-bearing zones are bedding-plane separations that probably provide pathways for contaminant transport in the bedrock aquifer for significant distances.

In the Mahopac business district, a deep test well completed in Precambrian gneiss intersected shallow water-bearing zones at 50 to 79 feet that produced contaminated water that was received by deep zones at 260 and 328 feet. The water-bearing zones consist of single or closely spaced multiple fractures with dips of 5 to 50 degrees. By analogy with the results from this test well, deep open-hole wells in the area may serve as "short circuits" in the ground water flow system and allow direct transport of contaminants to deeper zones in the fractured-bedrock aquifer.

The methods presented can be used to investigate ground water flow and contamination in fractured-bedrock aquifers in advance of more focused monitoring programs. The methods can be applied in existing open-hole wells before test drilling and monitoring well installation to provide for efficient program design. The methods also can be used during the installation of monitoring wells to help determine completion depths and open intervals and to ensure that the wells are not serving as conduits for the flow of contaminated water.

Introduction

Contamination by volatile organic compounds has affected many fractured-bedrock aquifers in the northeastern United States. Most wells completed in fractured-bedrock aquifers have only shallow surface casing and are open to multiple water-bearing zones. Vertical flow commonly occurs within open-hole wells between fracture zones of differing hydraulic head as a result of natural head gradients or gradients caused by nearby pumping. These wells serve as "short circuits" that connect shallow and deep water-bearing zones and thus may serve as conduits for the direct transport of contaminants between zones. Water-quality sampling at open-hole bedrock wells by traditional pumping or bailing methods may indicate the presence of volatile organic compounds but provides little information on the vertical distribution of contaminated water-bearing fractures.

In 1988-89, the U.S. Geological Survey (USGS) used a combination of geophysical logging, vertical-flow measurements, and downhole sampling to provide preliminary information on the distribution of contaminated water-bearing fractures intersected by open-hole bedrock wells as part of several remedial site investigations by the New York State Department of Environmental Conservation (NYSDEC). This paper describes the methods used and presents the results obtained at two of the study sites in southeastern New York — Spring Valley wellfield and Mahopac business district (Figure 1).

Methods

A suite of geophysical logs was completed in the wells to identify the bedrock lithology, distribution of water-bearing fractures, and the presence of vertical flow. Vertical-flow measurements were made to define the direction and rate of flow between water-bearing fractures that intersect the wells. A downhole sampler was used to collect water samples from depths selected according to the location of water-bearing fractures and the direction of flow between them. The water samples were analyzed for volatile organic compounds by the NYSDEC laboratory or by NYSDEC contractors in the field with a portable gas chromatograph.

The application of geophysical logging to ground water investigations is described by Keys (1988). The geophysical logs used in this investigation included gamma, single-point resistance, caliper, fluid resistivity, temperature, and acoustic televiewer. The geophysical logs, except for the acoustic televiewer, were recorded simultaneously on an analog chart and on digital tape at 0.1- or 0.5-foot sampling intervals. The acoustic-televiewer logs were recorded with a still camera or videocassette recorder. Characteristics of the geophysical logs are described next.

These methods can be used to investigate ground water flow and contamination.

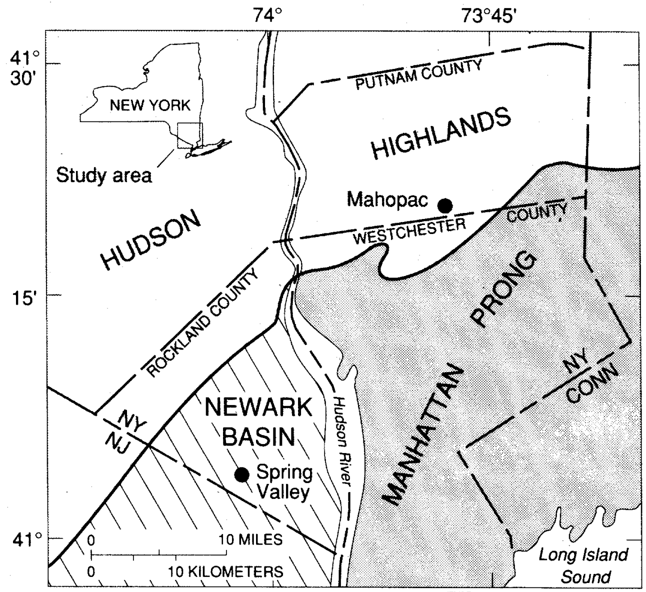

Figure 1. Location of study sites and physiographic provinces in southeastern New York.

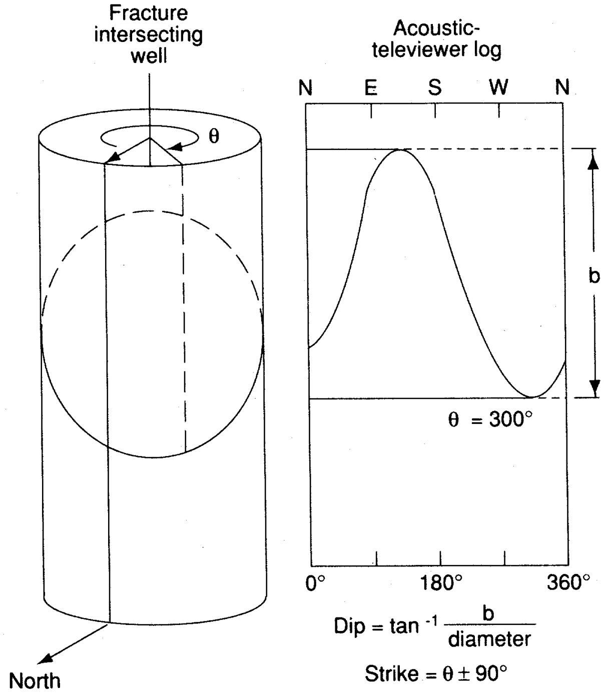

Figure 2. Fracture intersecting a well and corresponding acoustic-televiewer log and determination of strike and dip (modified from Paillet, 1985).

Gamma logs record the amount of naturally occurring gamma radiation emitted by the rocks surrounding the borehole. Most of the gamma radiation from rocks is emitted by potassium-40 and daughter products of the uranium- and thorium-decay series. Clay-bearing rocks emit relatively high gamma radiation because potassium is abundant in mica and clays, which are common decomposition products of potassium feldspars, and uranium and thorium are concentrated in clays by adsorption and ion exchange (Keys 1988). Feldspathic and uranium-rich zones in crystalline rocks, such as pegmatites, also emit relatively high gamma radiation.

Single-point resistance logs record the electrical resistance from points within the borehole to an electrical ground at land surface. In general, resistance increases with grain size and decreases with borehole diameter, density of water-bearing fractures, and dissolved-solids concentration of the water (Keys and MacCary 1971). Single-point resistance logs are useful in the determination of lithology, water quality, and location of fracture zones. In a study of a crystalline-bedrock aquifer in Canada, Paillet and Hess (1987) reported that the single-point resistance log provided the least ambiguous indication of fracture zones of any of the conventional logs.

Caliper logs record borehole diameter and are useful indicators of changes in borehole diameter related to construction (such as casing or drilling-bit size) and fracturing or caving of rocks along the sides of the borehole. Correlation of caliper logs with fluid-resistivity and temperature logs indicates the location of water-bearing fractures.

Fluid-resistivity logs record the electric resistance of water in the borehole. Changes in fluid resistivity reflect differences in dissolved-solids concentration of water. Because water from one fracture zone in a well commonly differs chemically from that in another zone, fluid-resistivity logs are useful in the delineation of water-bearing fractures.

Temperature logs record the water temperature in the borehole. Temperature logs are useful for the delineation of water-bearing fractures and identification of vertical flow between zones of differing hydraulic head. Flow between producing and receiving zones is indicated by temperature gradients of less than the regional geothermal gradient, which is about 1 F (0.56 C) per 100 feet (Carswell and Lloyd 1979, Williams and others 1984).

Water samples were collected for field analysis with a downhole sampler.

Acoustic-televiewer logs record a magnetically oriented, photographic image of the acoustic reflectivity of the borehole wall. Acoustic-televiewer logging is an ultrasonic method that was developed by the petroleum industry (Zemanek and others 1969) and has been applied to ground water investigations in fractured bedrock by Keys (1984) and Paillet and others (1985). The acoustic-televiewer indicates the location and strike and dip of fractures intersecting a well (Figure 2).

The direction and rate of vertical flow in the well were calculated from velocity measurements and borehole diameter recorded by the caliper log. Velocity measurements were made by the brine-tracing method described by Patten and Bennett (1962) or by a high-resolution, heat-pulse flowmeter developed by Hess (1982). The heat-pulse flowmeter, which was developed from a design by Dudgeon and others (1975), has been used by Hess (1984, 1986), Keys (1984), and Paillet and others (1987) to define low-velocity, vertical flow in open-hole bedrock wells.

A downhole sampler was used to collect discrete and composite water samples from self-purging producing zones, defined by the geophysical logs and flow measurements, for analysis of volatile organic compounds. The downhole sampler is a piston-driven device that is remotely controlled with the geophysical logger to collect a small volume of water at a specified depth. Where flow was downward from a producing zone and a no-flow boundary was present above the zone, a discrete sample of water produced by the zone was collected from below the zone. Where flow was upward and a no-flow boundary was present below the producing zone, a discrete sample was collected from above the zone. Composite samples were collected from depth intervals in which more than one producing zone contributed flow.

Case Studies

Spring Valley

The Spring Valley Water Co. has a major wellfield in the town of Spring Valley in south-central Rockland County (Figure 1). The wellfield lies within the Newark Basin, which is underlain by Mesozoic sedimentary bedrock consisting of interbedded conglomerate, sandstone, and shale. The wellfield includes six open-hole wells, 250 to 500 feet deep, which has produced over 2.8 million gallons per day (mgd), the largest pumpage from a bedrock aquifer in New York state. The volatile organic compounds, trichloroethylene (TCE) and tetrachloroethylene (PCE), were found in the supply wells in the late 1970s (Slayback and Rothenberg 1984). Well Ro82 (Spring Valley supply well 2), near the center of the wellfield, was geophysically logged and sampled to help estimate the vertical distribution of contamination in the fractured-bedrock aquifer. Five bedrock monitoring wells, which were completed as open holes in 1987-88 as part of NYSDEC remedial work, also were geophysically logged.

Well Ro82, which is 445 feet deep and has a reported yield of 350 gallons per minute (gpm) was retired from regular service in the early 1980s. At that time, the average TCE concentration at the well was 40 μg/L (micrograms per liter) and the average PCE concentration was 10 μg/L (Slayback and Rothenberg 1984). Average TCE concentrations at the five other supply wells were 5 to 55 μg/L and average PCE concentrations were 3 to 15 μg/L.

Although no geologic log of well Ro82 was available, the driller's log from a nearby supply well (Perlmutter 1959) and drill-core logs of the bedrock monitoring wells (GHR Engineering Associates 1989) indicate that the Mesozoic bedrock in the area consists of sandstone and conglomerate. Mesozoic sandstone and conglomerate are exposed in roadcuts one to two miles south and southwest of the wellfield. The exposed bedrock, which strikes north to N.45° E and dips westward 5 to 15° (N.M. Ratcliff, USGS written communication, 1989), generally is massive except for bedding-plane separations that range from 3 to more than 10 feet apart. At a major roadcut along Interstate 87, the dipping bedding-plane separations appear to be continuous along their length of exposure of more than 200 feet. Along

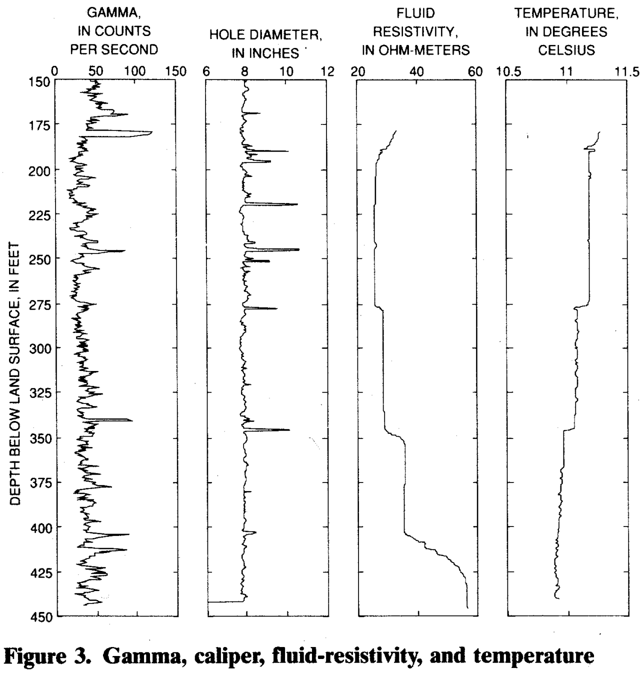

Figure 3. Gamma, caliper, fluid-resistivity, and temperature logs of well Ro82 at Spring Valley.

this roadcut, friable clayey sandstone is discontinuously present below some bedding-plane separations, and seepage from bedding-plane separations was observed in several areas.

Gamma, caliper, fluid-resistivity, and temperature logs were completed in well Ro82 (Figure 3). At the time of logging, the pumping rate from the wellfield was about 2.4 mgd, and the water level in the well was 179 feet below land surface. Correlation of spikes on the caliper log with slope changes on the fluid-resistivity and (or) temperature logs indicates that the well intersects water-bearing fractures at depths of 190, 204, 220, 245, 278, 345, and 403 feet (Figure 4). Many of the water-bearing fractures appear to be associated with changes on the gamma log. Zones of higher gamma radiation are present below the water-bearing fractures at 245 and 403 feet. These zones may be friable clayey sandstone

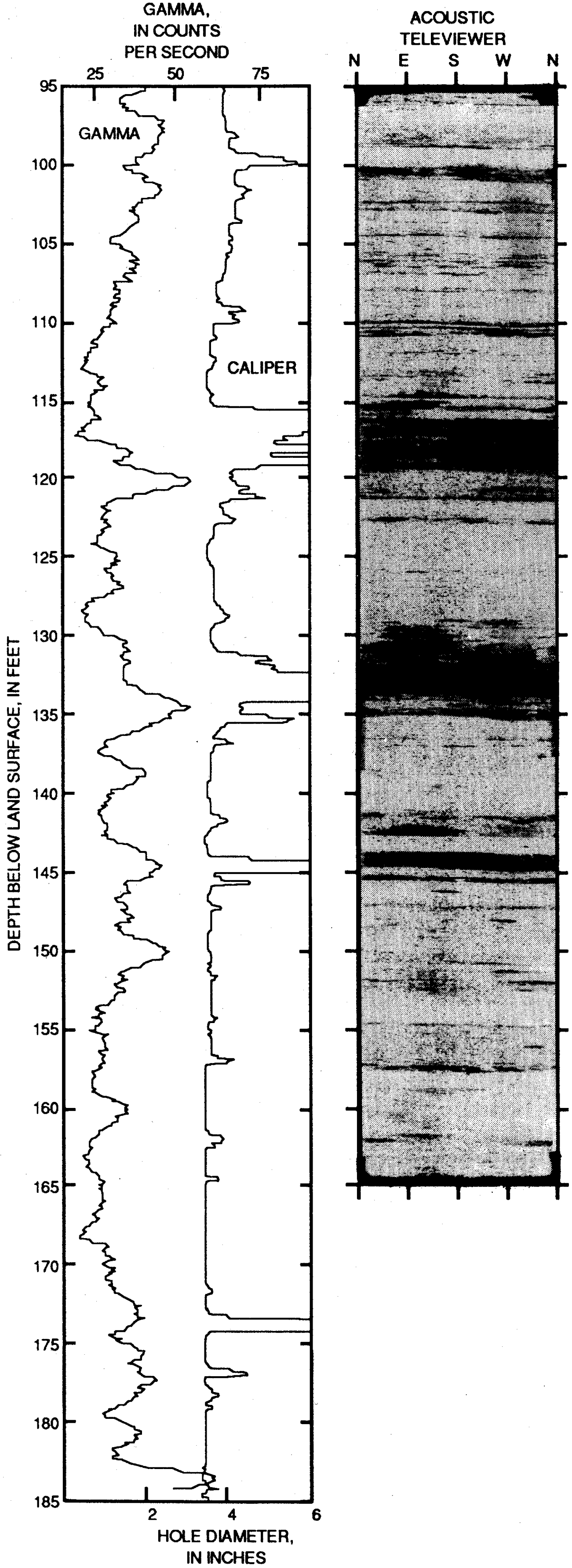

Figure 4. Gamma, caliper, and acoustic-televiewer logs of well Ro542 at Spring Valley.

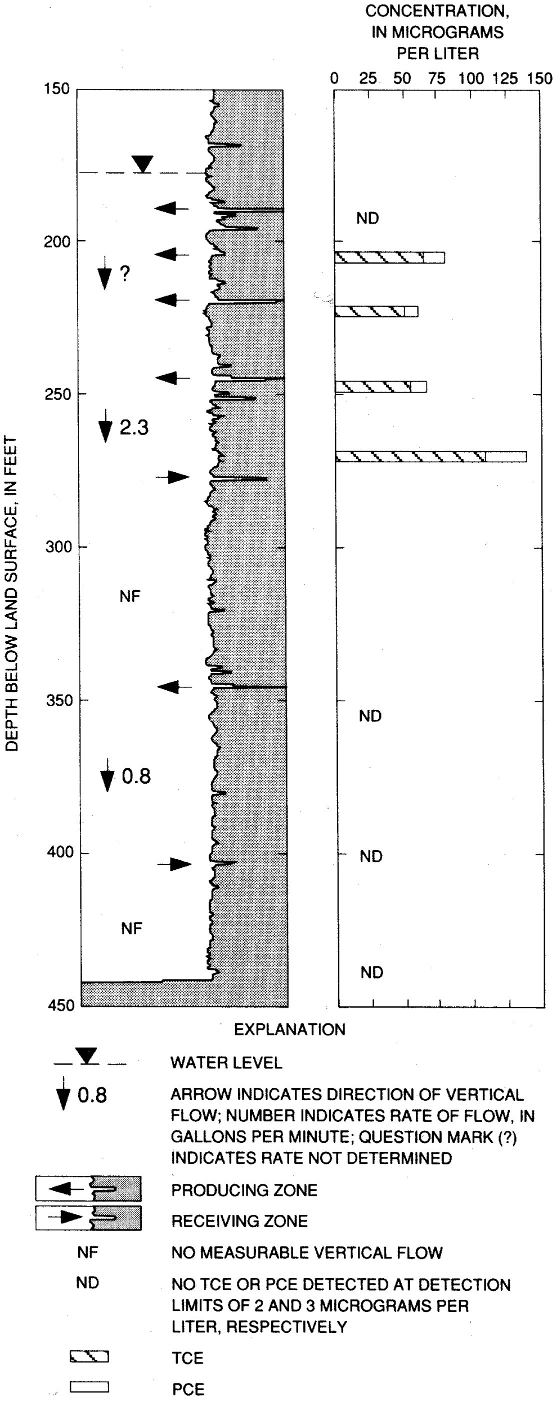

Figure 5. Vertical-flow direction and rate and TCE and PCE concentrations in well Ro82 at Spring Valley.

similar to that found below some of the bedding-plane separations at the major roadcut along Interstate 87.

Drill-core recovery from fractured intervals in the bedrock monitoring wells generally was poor, although friable clayey sandstone was recovered from two fracture zones. Many of the fracture zones in the bedrock monitoring wells also are associated with changes on the gamma logs. Gamma, caliper, and acoustic televiewer logs of the monitoring well Ro542, which is about 1500 feet south of well Ro82, are presented in Figure 4. The acoustic-televiewer log of the well Ro542 indicates that fracture orientation is consistent with bedding strike and dip in the area, which further suggests that the intersected fractures are bedding-plane separations.

The application of geophysical logging to ground water investigations was described by Keys.

Intervals of isothermal slope on the temperature log and slope changes on the temperature and (or) fluid-resistivity logs indicate vertical flow in well Ro82 and significant changes in flow at depths of 287, 345, and 403 feet (Figure 3). Flow measurements were made in the well by the brine-tracing method at depths of 210, 255, 310, 375, and 425 feet (Figure 5). Flow at 255 feet was downward at a rate of 2.3 gpm. Flow at 210 feet, although below the reliable measurement limit, also appeared to be downward. Changes are present on the fluid-resistivity log at 190, 204, 245, and 278 feet. No measurable flow was detected at 310 feet. These data suggest that several fracture zones above 250 feet are the producing zones of this downward flow and that the fracture zone at 278 feet is the receiving zone for essentially all of this flow.

Flow at 375 feet was downward at a rate of 0.8 gpm, and no measurable flow was detected at 425 feet (Figure 5). Slope changes on the fluid-resistivity log at 345 and 403 feet (Figure 3), and the lack of significant flow at 310 and 425 feet, indicate that the fractures at 345 and 403 feet are the producing and receiving zones, respectively, for this downward flow.

Water samples were collected for field analysis of volatile organic compounds with a downhole sampler in the supply well at depths of 192, 205, 223, 247, 270, 355, 400, and 440 feet (Figure 5). Samples from 205, 223, 247 and 270 feet contained TCE concentrations of 64, 50, 54, and 110 µg/L, and PCE concentrations of 15, 10, 12, and 28 µg/L, respectively (F.B. Stevenson, GHR Engineering Associates, written communication, 1988). These results suggest that fractures at 204, 220, and 245 feet produced water with TCE and PCE concentrations of about 55 and 12 µg/L, respectively, and that the fracture zone at 278 feet is the receiving zone for the contaminated water

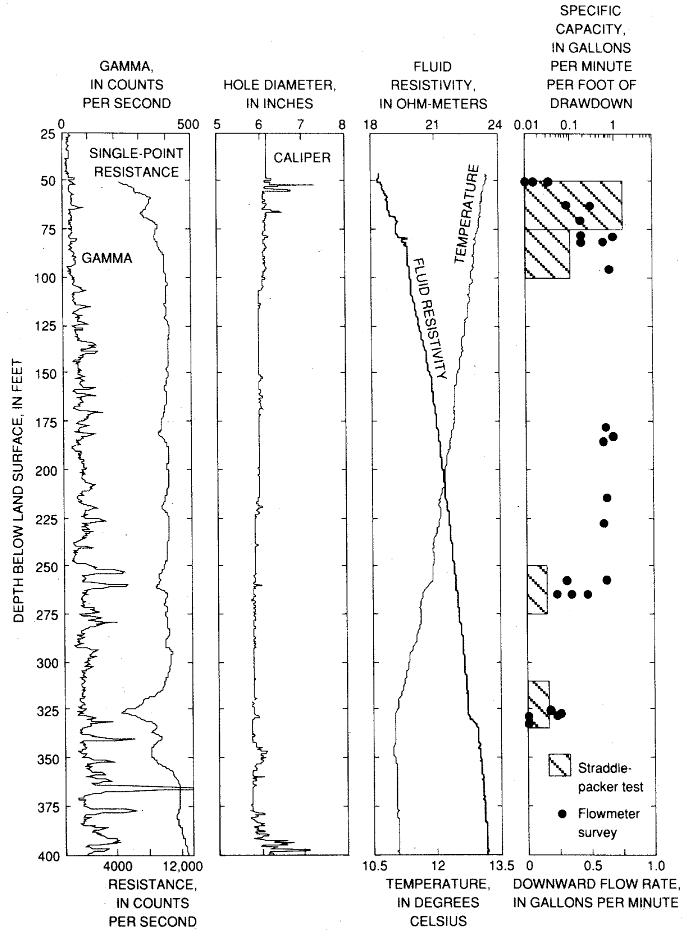

Figure 6. Gamma, single-point resistance, caliper, fluid-resistivity, and temperature logs; vertical flow as measured with the heat-pulse flowmeter; and specific capacity as measured by straddle-packer pumping tests of well P899 at Mahopac.

The source of elevated TCE and PCE concentrations in the 270-foot-deep sample was not identified (Figure 5). Possibly, fractures at depths of 250, 252, 254, and (or) 257 feet produced water that is even more highly contaminated, but the fluid-resistivity and temperature logs do not indicate flow from any of these zones. Another possibility is that the elevated concentrations are the result of an analytical error. The source of uncontaminated water at 192 feet also was not identified; water from fractures above this depth may not be contaminated. Additional flow measurements and water-quality sampling and analysis would be needed to resolve these questions.

The water sample collected at 355 feet was a discrete sample of the downward flow from the producing zone at 345 feet because flow between 278 and 345 feet appears negligible (Figure 5). No volatile organic compounds were detected in this sample nor in samples collected at 400 and 440 feet. The fracture zone at 345 feet apparently produces uncontaminated water that is received by the zone at 403 feet.

Results of the logging, flow measurements, and sampling indicate that the water-bearing fractures in well Ro82 at depths of 204 to 278 feet are contaminated with volatile organic compounds. The distribution of bedding-plane separations intersected by well Ro542 at depths of 100 to 174 feet (Figure 4) is similar to that of those zones intersected by well Ro82 at depths of 204 to 278 feet (Figure 3). Composite pumped samples from well Ro542, about 1500 feet south of well Ro82, had an average TCE concentration of 50 µg/L and an average PCE concentration of 23 µg/L (GHR Engineering Associates 1989; J.Clyne, NYSDEC, written communication, 1989). These average concentrations of TCE and PCE are similar to those in samples from the contaminated interval at well Ro82. This information suggests that water-bearing fractures along bedding-plane separations provide pathways for contaminant transport in the bedrock aquifer for significant distances.

Mahopac

The Mahopac business district, in south-central Putnam County, is supplied by private and shared wells completed as open holes in fractured bedrock (Figure 1). Mahopac lies within the Hudson Highlands, an area underlain by highly resistant metamorphic bedrock of Precambrian age, predominantly gneiss with some amphibolite, marble, and quartzite. Feldspathic intrusions are common in the gneiss.

PCE and TCE contamination was found in several supply wells in the Mahopac business district during 1978-79. In 1988, a deep test well (P899) was installed as part of NYSDEC remedial work to investigate the vertical distribution of contamination in the fractured-bedrock aquifer. The test well reportedly yielded more than 50 gpm, penetrated 23 feet of glacial drift and 2 feet of weathered bedrock, and was cased to 50 feet. The bedrock penetrated by the test well consists of foliated to banded granitic gneiss. The test well was geophysically logged at a completion depth of 220 feet during a temporary shutdown of drilling operations and was logged and sampled at its final completion depth of 400 feet.

The water level in well P899 is affected by pumping from wells that supply local businesses. At the time of logging, the water level in the test well fluctuated between 8 and 11 feet below land surface. A continuous record of water levels in the test well (Wehran Engineering 1990) shows several feet of drawdown during the morning hours, recovery-drawdown cycles of 0.5 feet in the afternoon and early evening, and then recovery after business hours at night.

Gamma, single-point resistance, caliper, fluid-resistivity, temperature, and acoustic-televiewer logs were completed in well P899 (Figures 6 and 7). The gamma log indicates 1- to 5-foot-thick zones with increased radioactivity, which are most prevalent between 250 to 400 feet below land surface. Notable gamma peaks, which indicate feldspathic zones, are at 253, 260, 280, 330, 340, 352, 366, 377, and 395 feet. Lower gamma counts are associated with the more mafic zones, and intermediate gamma counts indicate banded gneiss.

The single-point resistance, caliper, and acoustic-televiewer logs indicate that the test well intersected fracture zones at depths of 50 to 55, 66, 79, 180, 220, 260, and 328 feet (Figures 6 and 7). The fractures zones consist of a single fracture or a series of closely spaced fractures. The acoustic-televiewer log indicates that spikes on the caliper log between 350 and 400 feet were irregular fractures and planar fractures that appeared to be only partly open.

At a completion depth of 200 feet, the brine-tracing method revealed no vertical flow in the test well but at a completion depth of 400 feet, the fluid-resistivity and temperature logs indicate vertical flow and a major change in flow conditions at 328 feet (Figure 6). A heat-pulse flowmeter survey (F.L. Paillet, USGS, written communication, 1988) defined downward flow from shallow producing zones to deep receiving zones (Figures 6 and 7). Maximum downward flow during the survey, which was completed in the early evening, ranged from 0.31 to 0.70 gpm, apparently in response to intermittent pumping.

Fractures at a depth of 50 to 55 feet produced from 50 to more than 80 percent of the downward flow; the rest was produced by fractures at 66 and 79 feet (Figures 6 and 7). About 25 percent of the downward flow was received by the fracture zone at 260 feet; the rest was received by the fracture zone at 328 feet. The change from downward flow to no flow correlates with the sharp break in the fluid-resistivity and temperature logs at 328 feet.

Slug-recovery and specific-capacity data collected by Earth Data (L.F. Coddington, Wehran Engineering, written communication, 1988) with a 25-foot straddle-packer injection and pumping system indicate that the more transmissive intervals intersected by the test well

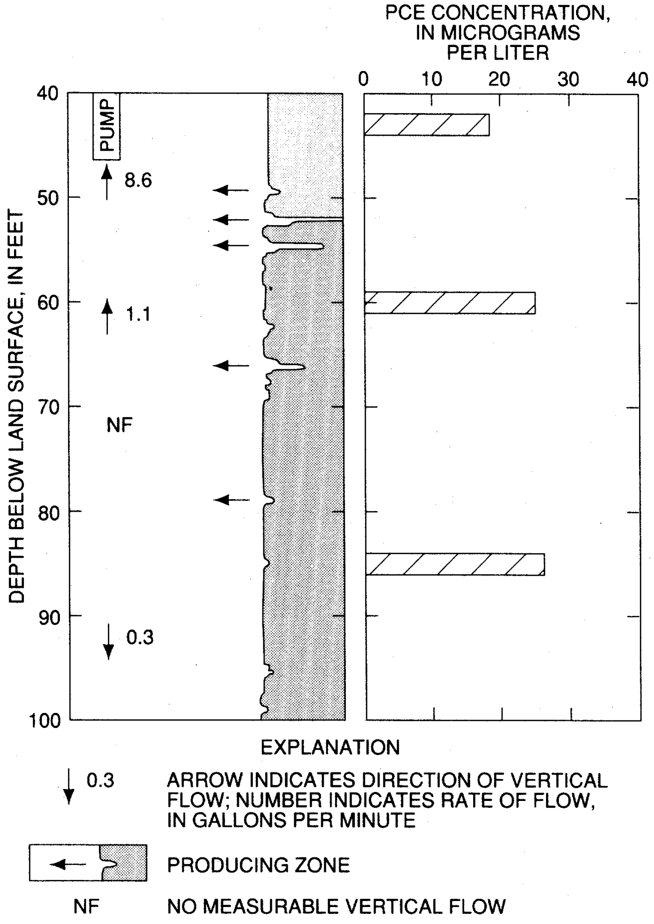

Figure 8. Vertical-flow direction and rate as measured by brine tracing and PCE concentration in the upper part of well P899 at Mahopac during pumping.

were from depths of 50 to 100 feet (50 to 55-, 66-, 79-foot-deep zones), 250 to 275 feet (260-foot-deep zone), and 310 to 335 feet (328-foot-deep zone). The combined specific capacity of the shallow producing zones is about 30 times that of the deep receiving zones (Figure 7). Water-level measurements made during the straddle-packer tests indicated that the heads in the shallow zones were about 2 feet higher than those in the deep zones.

Water samples were collected with the downhole sampler for laboratory analysis of volatile organic compounds in the test well at depths of 57, 82, 140, 180, 230, 340, and 380 feet below land surface. Analysis of the sample collected at 57 feet (Wehran Engineering 1990) indicates that the fractures at 50 to 55 feet produced water with a PCE concentration of 17 μg/L. The sample collected at 82 feet had a PCE concentration of 25 μg/L, which suggests that the fractures at 66 and 79 feet probably produced similarly contaminated water. As would be expected with the downward flow from the shallow producing zones to deep receiving zones, water samples collected at 140, 180, and 230 feet had PCE concentrations similar to those in the sample from the 82-foot depth — 24 to 33 μg/L. Water samples collected at 340 and 380 feet, which is below the receiving zone at 328 feet and in a no-flow interval, also had similar PCE concentrations. This contamination probably was residual caused by mixing of borehole water during drilling and development.

Vertical flow commonly occurs within open-hole wells between fracture zones of differing head.

A submersible pump was set at a depth of 50 feet, and the well was pumped at 9.7 gpm to ascertain whether the fractures at 66 and 79 feet produced contaminated water. Repeated vertical-flow measurements were made by the brine-tracing method until the flow stabilized and a no-flow boundary was created between the two fracture zones (Figure 8). Analysis of water samples collected with a downhole sampler at 60 and 85 feet after purging of the borehole interval indicated that the 66- and 79-foot-deep zones produced water with PCE concentrations of 25 and 26 μg/L, respectively.

The fractures at depths of 50 to 55, 66, and 79 feet produced water with similar contaminant concentrations that flowed downward to deep receiving zones at 260 and 328 feet. As would be expected from the flow conditions in the test well, water sampled from the shallow and deep zones during straddle-packer pumping tests, which were only 0.5 hours in duration, had contaminant concentrations similar to those in the downhole samples (Wehran Engineering 1990).

In the absence of open-hole wells, the deep water-bearing fractures intersected by the test well as 260 and 328 feet may not be connected with the contaminated part of the shallow bedrock aquifer. At the test-well site, the shallow bedrock aquifer consists of an interconnected network of fractures at a depth of less than 80 feet that dip 5 to 50° (Figure 7). The 260-foot-deep zone intersected by the test well is a single fracture that dips about 25° northwestward, and the 328-foot-deep zone consists of four subparallel fractures between 327 and 329 feet that dip 20 to 50° southwestward.

Subsequent to the logging and sampling, Wehran Engineering installed a shallow monitoring well and a deep monitoring well in the fractured-bedrock aquifer at the test-well site. The shallow monitoring well, which is screened and sand-packed at a depth of 40 to 70 feet, is open to the 50 to 55- and 66-foot-deep zones as well as any additional water-bearing fractures between 40 to 50 feet. The deep monitoring well, which is screened and sand-packed at a depth of 310 to 340 feet, is open to the fracture zone at 328 feet. Water-level measurements made during daytime business hours (Wehran Engineering 1990) indicate that the head in the 328-foot zone generally is 1.5 to 3 feet lower than that in the shallow zones and that most of the temporal variation in the head difference was due to fluctuations in the deep zone. Drawdown associated with pumping of nearby wells open to the deep zones apparently was a major cause of the downward flow in the test well. By analogy, information from the test well suggests that deep open-hole wells in the Mahopac business district may serve as "short circuits" in the ground water flow system connecting shallow and deep aquifer zones. Local pumping from deep aquifer zones causes lowered heads at depth, which could result in direct downward transport of contaminants in the open-hole wells.

Conclusions and Applications

A combination of geophysical logging, vertical-flow measurements, and downhole sampling proved to be an effective method for the preliminary investigation of volatile organic contamination in open-hole bedrock wells in southeastern New York. The methods involved less than two days of field work per well site and provided information on the distribution of water-bearing fractures and the direction and rate of vertical flow between fractures. On-site analysis of water samples with a portable gas chromatograph allowed preliminary delineation of contaminated water-bearing fractures in the field. Digital recording of the geophysical-log data facilitated subsequent analysis and presentation of information by use of computer-generated graphics.

The methods presented in this paper can be used to investigate ground water flow and contamination in fractured-bedrock aquifers in advance of more focused monitoring programs. The methods can be applied in existing open-hole wells before test drilling and monitoring well installation to provide for efficient program design. Much information can be collected without disturbing the ground water flow system or producing large volumes of contaminated waste water or drill cuttings that require disposal. The downhole information collected by these methods is useful in the design and interpretation of straddle-packer tests. The methods also can be used during the installation of monitoring wells to help determine completion depths and open intervals and to ensure that the wells are not serving as conduits for the flow of contaminated water.

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Author's Note

Use of firm names in this report is for identification purposes only and does not constitute endorsement by the USGS.

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