An Integrated Geophysical and Hydraulic Investigation to Characterize a Fractured-Rock Aquifer, Norwalk, Connecticut

Water-Resources Investigations Report 01-4133

Prepared in cooperation with the United Technologies Corporation

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

Front cover: Optical televiewer image projected flat (left) and as a “virtual core” (right), borehole MW-69, Norwalk, Connecticut.

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By John W. Lane Jr., John H. Williams, Carole D. Johnson,
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Storrs, Connecticut
2002

U.S. DEPARTMENT OF THE INTERIOR
GALE A. NORTON, Secretary

U.S. GEOLOGICAL SURVEY
Charles G. Groat, Director

For additional information write to:

Branch Chief
U.S. Geological Survey
11 Sherman Place, U-5015
Storrs, CT 06269
http://water.usgs.gov/ogw/bgas

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CONVERSION FACTORS AND ABBREVIATIONS

Multiply	By	To obtain
feet (ft)	0.3048	meters
inches (in.)	25.4	millimeters
acre	4047.	square meters
feet per nanosecond (ft/ns)	304.8	meters per microsecond
square feet per day (ft^2/d)	0.0929	square meters per day
gallons per minute (gal/min)	3.786	liters per minute
gallons per minute, per foot ((gal/min)/ft)	12.422	liters per minute, per meter

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:
°C = (°F-32)/1.8

Other abbreviations used in this report:

°, degrees
MHz, megahertz

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ABSTRACT

The U.S. Geological Survey conducted an integrated geophysical and hydraulic investigation at the Norden Systems, Inc. site in Norwalk, Connecticut, where chlorinated solvents have contaminated a fractured-rock aquifer. Borehole, borehole-to-borehole, surface-geophysical, and hydraulic methods were used to characterize the site bedrock lithology and structure, fractures, and transmissive zone hydraulic properties. The geophysical and hydraulic methods included conventional logs, borehole imagery, borehole radar, flowmeter under ambient and stressed hydraulic conditions, and azimuthal square-array direct-current resistivity soundings.

Integrated interpretation of geophysical logs at borehole and borehole-to-borehole scales indicates that the bedrock foliation strikes northwest and dips northeast, and strikes north-northeast to northeast and dips both southeast and northwest. Although steeply dipping fractures that cross-cut foliation are observed, most fractures are parallel or sub-parallel to foliation. Steeply dipping reflectors observed in the radar reflection data from three boreholes near the main building delineate a north-northeast trending feature interpreted as a fracture zone. Results of radar tomography conducted close to a suspected contaminant source area indicate that a zone of low electromagnetic (EM) velocity and high EM attenuation is present above 50 ft in depth - the region containing the highest density of fractures. Flowmeter logging was used to estimate hydraulic properties in the boreholes. Thirty-three transmissive fracture zones were identified in 11 of the boreholes. The vertical separation between transmissive zones typically is 10 to 20 ft.

Open-hole and discrete-zone transmissivity was estimated from heat-pulse flowmeter data acquired under ambient and stressed conditions. The open-hole transmissivity ranges from 2 to 86 ft^2/d. The estimated transmissivity of individual transmissive zones ranges from 0.4 to 68 ft^2/d. Drawdown monitoring in nearby boreholes under pumping conditions identified hydraulic connections along a northeast-southwest trend between boreholes as far as 560 ft apart. The vertical distribution of fractures can be described by power law functions, which suggest that the fracture network contains transmissive zones consisting of closely spaced fractures surrounded by a less fractured and much less permeable rock mass.

INTRODUCTION

The U.S. Geological Survey (USGS) conducted a geophysical and hydraulic investigation to characterize a contaminated fractured-bedrock aquifer at the Norden Systems, Inc. (NSI) site in Norwalk, Connecticut using an integrated “toolbox” approach. The toolbox approach to characterization of fractured-rock aquifers was developed as part of multidisciplinary hydrogeologic investigations at the USGS Toxic Substances Hydrology Program fractured-rock field research site at Mirror Lake, Grafton County, N.H. The toolbox approach follows the hierarchical approach described by Shapiro and others (1999) that integrates borehole- to regional-scale hydrogeologic information from a broad range of earth-science disciplines to characterize the hydrogeology of fractured-rock aquifer sites. The geophysical component of this approach combines multiple borehole- and surface-geophysical methods to remotely measure rock, fracture, and hydraulic properties over a range of scales, consistent with the study objectives, site conditions, and physical dimensions of the problem.

Purpose and Scope

This report presents results of an integrated geophysical and hydraulic investigation to characterize a contaminated fractured-bedrock aquifer site in Norwalk, Connecticut. The USGS conducted the investigation as part of a Cooperative Research and Development Agreement with United Technologies Corporation (UTC) to develop and test geophysical methods to investigate bedrock hydrogeology and to monitor active and innovative remediation measures. The purpose of this geophysical and hydraulic investigation was to characterize the bedrock lithology and structure at the site and to identify the orientation, distribution, and hydraulic characteristics of fractures and transmissive zones in the fractured-bedrock aquifer. This work supported ongoing efforts to develop a conceptual site model of ground-water flow and solute transport and to design a discrete-zone monitoring (DZM) and sampling network.

Conventional borehole logging, borehole-wall imaging, flowmeter, radar reflection logging, cross-hole radar tomography, and surface azimuthal square-array resistivity sounding methods were used in this investigation. The selected geophysical methods measure variations in subsurface properties over borehole (10^{-3} to 10^{-1} ft), near-borehole (10^{-1} to 10^{1} ft), hole-to-hole (10^{1} ft), and surface (10^{1} to 10^{2} ft) scales.

Description of the Study Area

The geophysical investigations were conducted at the 78.6-acre NSI site in Norwalk, Connecticut (fig. 1). The site is underlain by fractured granitic gneiss and micaceous schist of Cambrian-Ordovician age locally intruded by pegmatite (Kroll, 1977). Bedrock outcrops bound the northern and southern property boundaries; additional outcrops are exposed at other locations on or near the site. The bedrock surface at the site slopes to the southeast. Unconsolidated glacial-drift deposits up to 30 ft thick overlie a zone of moderately to highly weathered bedrock. Near the main building (fig. 2), the depth to rock generally is less than 5 ft.

Manufacturing operations conducted from the early 1960s to the early 1980s used chlorinated solvents, primarily for degreasing, and these solvents have contaminated the ground and ground water beneath the site. As part of voluntary environmental investigations by the property owners, a network of monitoring wells was installed in the unconsolidated deposits, weathered bedrock, and shallow portions (up to 60 ft below ground surface) of the more competent fractured bedrock. Concentrations of dissolved solvents exceeding Connecticut State regulatory limits were detected in all three zones. Two plumes of solvent-contaminated ground water have been delineated in the unconsolidated deposits and shallow bedrock. One plume emanates from within the main building near the location of a former degreaser pit; the other from a loading dock at a former hazardous-waste storage area just outside the main building (fig. 2).

Acknowledgments

The authors gratefully acknowledge the many people who provided assistance with geophysical logging and analysis including Alton

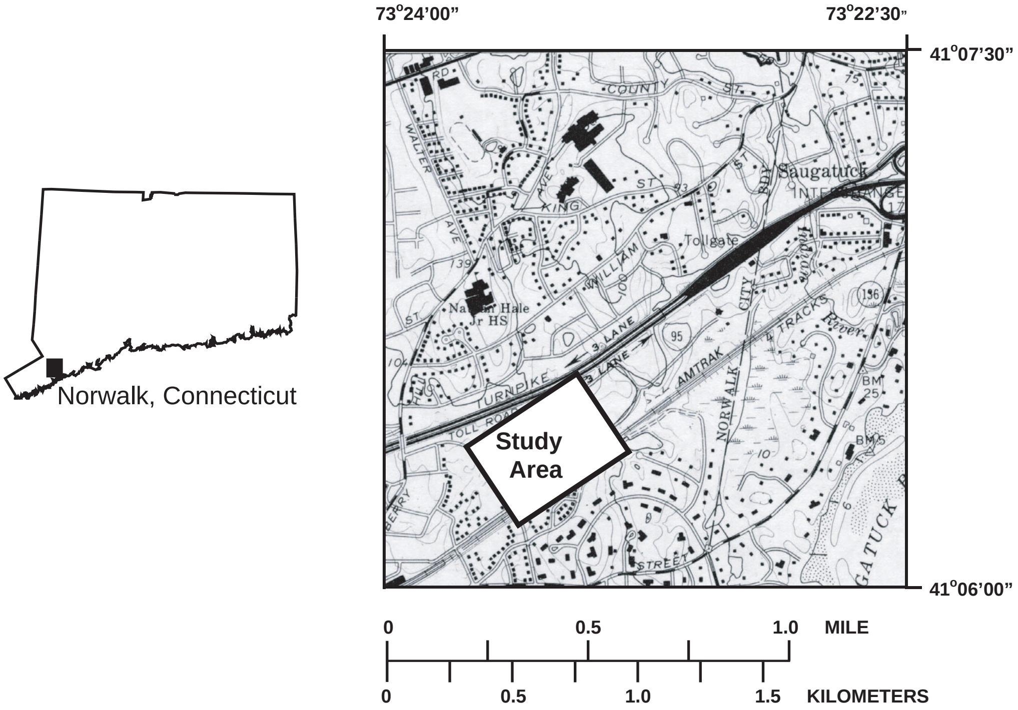

Figure 1. Location of the study area, Norwalk, Connecticut.

Anderson, Marcel Belaval, Marc Buursink, Peter Joesten, C.J. Powers, Kamini Singha, Eric White, and Jody Wilson of the U.S. Geological Survey.

GEOPHYSICAL METHODS

Descriptions of the borehole- and surface-geophysical methods used for this investigation are provided in this section. The conventional borehole-geophysical logs used to measure physical properties of the rock include electromagnetic- (EM) induction, gamma, caliper, and borehole deviation. These methods provide preliminary information on borehole construction and conditions, lithology, and fractures (Keys, 1990). The borehole-wall imaging logs were used to obtain high-resolution images of lithology, structure, and fractures within boreholes. Radar reflection logs and cross-hole radar tomography were used to identify fracture zones surrounding boreholes, and to infer their presence between boreholes. On a larger scale, the surface azimuthal square-array resistivity method was used to determine the direction of apparent resistivity anisotropy.

Conventional Geophysical Logging

Electromagnetic-induction logging records the electrical conductivity or resistivity of the rocks and water surrounding the borehole (Williams and others, 1993). Electrical conductivity is affected by porosity, clay and metallic mineral content of the rocks, and dissolved solids concentration of the water. The induction probe is designed to maximize vertical resolution and radial penetration, and to minimize the effects of the borehole fluid. The induction probe has a vertical resolution of about 2 ft. In boreholes with diameters of 6 in. or less, the resistivity of the borehole fluid has a negligible effect on the induction-log response (Keys, 1990; Williams and others, 1993). The induction logs were used to help delineate changes in rock type.

Gamma logging records the amount of gamma radiation emitted by the rocks surrounding the borehole (Keys, 1990). The most common naturally occurring sources of gamma radiation are potassium-40 and daughter products of the uranium- and thorium-decay series. The vertical resolution of the gamma probe is 1 to 2 ft. The

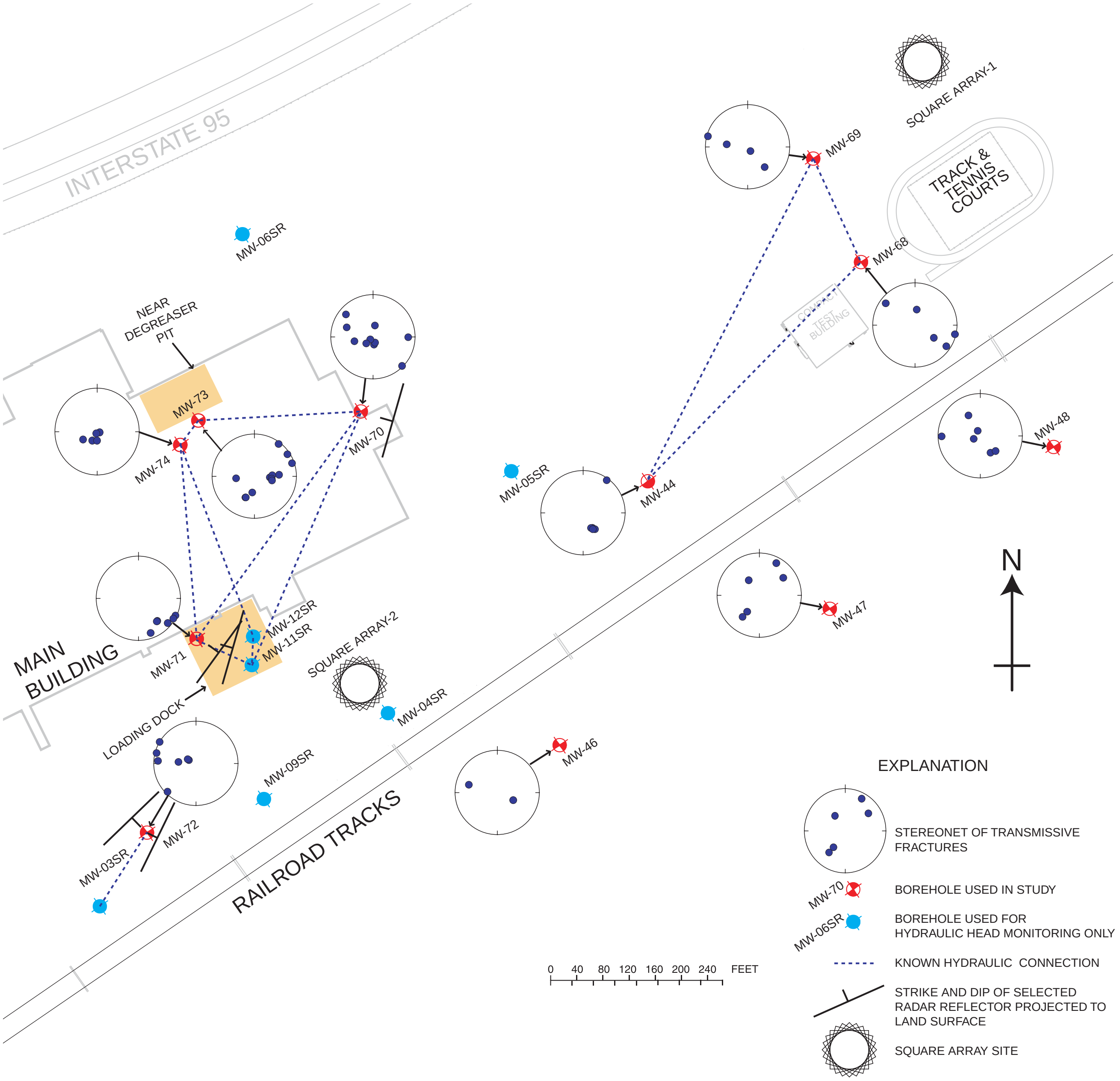

Figure 2. Study area in Norwalk, Connecticut, with borehole locations, equal-area stereonets showing the orientation of transmissive fractures, and lines representing known hydraulic connections between wells.

gamma logs were used to help delineate changes in rock type.

Caliper logging records borehole diameter by use of a three-arm, spring-loaded tool (Keys, 1990). Changes in borehole diameter are related to drilling and construction procedures, caving in of less competent rocks, and the presence of fractures. The caliper logs were used with the borehole-wall imaging, fluid resistivity, temperature, and heat-pulse flowmeter logs to characterize flow zones associated with fractures intersected by the boreholes.

Borehole-deviation logging records the three-dimensional location of a borehole (Keys, 1990). Knowledge of borehole deviation is important to determine the true location and orientation of planar features intersected by the borehole. Borehole deviation tools generally indicate borehole inclination to within ± 0.5° and direction to within ± 2°. The borehole-deviation data were used to correct the orientation of foliation and fractures identified on the borehole-wall imaging logs and to determine the location of cross-hole radar measurement stations.

Optical-Televiewer Logging

Optical-televiewer (OTV) logging records a magnetically oriented, 360° optical image of the borehole wall (Williams and Johnson, 2000). An OTV log can be viewed as an unwrapped image or it can be wrapped and viewed as a "virtual core." The OTV can be used in air or below the borehole water level if the water has low turbidity. The vertical and horizontal sampling intervals for the OTV images were 0.01 and 0.008 in., respectively. Fractures and other planar features nearly as small as the sampling interval can be detected. The location and orientation of fractures, foliation, and lithologic changes can be interpreted from OTV data. Because the OTV is an optical system, low optical contrast features, such as small fractures in dark rocks, can be difficult to delineate. Also, sediment, oxidation products, and biological activity that mask the borehole wall can degrade the quality of the OTV image. The OTV logs were analyzed to identify lithology and to determine the physical characteristics and orientation of foliation and fractures.

Borehole-Radar Reflection

Borehole-radar reflection methods utilize high-frequency EM waves in the 10- to 1,000-MHz range to detect fractures and fracture zones in the bedrock surrounding the borehole. These methods can detect radar reflectors that do not intersect the boreholes. In electrically resistive rocks, such as granite or gneiss, radial penetration of the radar waves can exceed 100 ft. At this site, radar waves penetrate as much as 70 ft. Borehole-radar reflection data are interpreted to determine the location and orientation of reflections from fracture zones, voids, and lithologic changes, and to estimate the radial extent of planar reflectors.

Cross-Hole Radar Tomography

Cross-hole radar tomography methods are used to estimate the EM properties in the plane between two boreholes (Olsson and others, 1992). For this investigation, the radar travel-time and amplitude were measured and inverted to create tomograms showing the radar propagation velocity and attenuation in the bedrock between two boreholes. Below the water table, decreases in velocity and increases in attenuation can indicate fracture zones and (or) lithologic changes.

Azimuthal Square-Array Direct-Current Resistivity Sounding

Azimuthal square-array direct current (dc)-resistivity soundings measure changes in apparent resistivity with direction and depth about the array center point. Apparent resistivity data measured by an azimuthally rotated square array over a homogeneous earth containing uniformly oriented, saturated, steeply dipping fractures, will have an apparent resistivity minimum oriented parallel to the dominant fracture orientation (Habberjam and Watkins, 1967; Lane and others, 1995). Where electrical-resistivity anisotropy is induced by bulk fracture or rock fabric orientation, azimuthal-resistivity methods are useful for estimating fracture and (or) foliation orientation trends.

HYDRAULIC METHODS

Fluid-resistivity, fluid-temperature, and heat-pulse flowmeter logs were used to determine the hydraulic properties and general water quality of the bedrock aquifer. These logs were collected under both ambient and hydraulically stressed conditions.

Fluid-Resistivity Logging

Fluid-resistivity logging records the electrical resistivity of the water in a borehole (Williams and Conger, 1990). The electrical resistivity of the water is the inverse of the specific conductance and is dependent on the dissolved-solids concentration. The fluid-resistivity logs were combined with the temperature and flowmeter logs to identify flow zones and to determine the relative dissolved-solids concentration of the water in the borehole under ambient and stressed conditions.

Temperature Logging

Temperature logging records the temperature of the water in the borehole (Williams and Conger, 1990). In boreholes with no ambient borehole flow, the temperature of the borehole water generally increases with depth as a function of the geothermal gradient in the surrounding rocks. Temperature gradients less than the geothermal may indicate intervals with flow into the borehole. Temperature logs were used with the fluid-resistivity and flowmeter logs to identify flow zones under ambient and stressed conditions.

Flowmeter Logging

Flowmeter logging is used to measure the direction and rate of movement of water in a borehole (Hess, 1986). The logs are used to identify vertical flow, establish relative hydraulic gradients, and identify transmissive fractures and zones. Stationary flow measurements are made under ambient and stressed conditions between fractures that have been identified in the caliper and OTV logs. The heat-pulse flowmeter (HPFM) used in this investigation is capable of resolving vertical flows from 0.01 ± 0.005 to 1 gal/min. Due to the operational design and calibration of the HPFM, flow estimates near the upper measurement range are approximate. Flowmeter logging conducted by Paillet (1998) consistently identified only those zones with transmissivities within 1.5 to 2.0 orders of magnitude of the most transmissive zone of each borehole. Therefore, the flowmeter technique used in this investigation is sufficient to identify only the more transmissive fractures in each borehole.

In fractured-rock investigations, it is important to conduct flowmeter logging under both ambient and stressed conditions. The composite head in an open hole is weighted by both the head and transmissivity of individual fracture zones, and preferentially weighted by the head of the most transmissive zone. Hence, the hydraulic logs, including fluid resistivity, temperature, and HPFM, were collected under ambient conditions and near-steady-state conditions at low pumping rates, typically 1 gal/min or less. The ambient and pumping water levels and fluid and HPFM logs were interpreted together to identify hydraulically active fractures and to estimate open-hole specific capacity and transmissivity and fracture-zone transmissivity and hydraulic head.

Cross-hole water-level and flowmeter measurements were made to identify potential cross-connections between boreholes. HPFM logs were collected in one borehole while another borehole was pumped at a rate of 1 to 3 gal/min. Water levels were measured in both boreholes during the flowmeter testing. The borehole acts as a short circuit and flow occurs between transmissive zones with differing hydraulic head. Water-level and flowmeter measurements are needed under the two hydrologic conditions to estimate transmissivity of individual fracture zones (Paillet, 1998).

ANALYSIS OF HYDRAULIC DATA

The hydraulic data acquired during flowmeter logging can be used to estimate specific capacity and transmissivity for open boreholes, and to estimate the transmissivity and hydraulic head of individual transmissive fractures and fracture zones.

Estimation of Specific Capacity and Transmissivity of Open Boreholes

Specific capacity and transmissivity of the open boreholes were estimated from the discharge and water-level data collected during flowmeter logging. Specific capacity is defined as

$$SC = Q/s,$$

where SC is the specific capacity in (gal/min)/ft,
Q is the pumped rate in gal/min, and
s is the drawdown in ft.

Estimates of open-hole transmissivity were calculated from the specific-capacity data based on a method described by Theis and others (1963). The relation between transmissivity and specific capacity is (Prudic, 1991)

$$T = 15.32\ (SC)\ (-0.577 - \log_e [(r^2S) / (4Tt)]),$$

where T is the transmissivity in ft^2/d,
r is the radius of borehole in ft,
S is the storage coefficient, and
t is the time in days.

Because the transmissivity term appears on both sides of the equation, the iterative process described by Bradbury and Rothschild (1985) was used to determine the transmissivity of the open boreholes.

Estimation of Transmissivity and Hydraulic Head of Fracture Zones

In boreholes with no measurable ambient flow, the open-hole transmissivity was apportioned to individual transmissive fracture zones according to the relative contribution of each zone to the total flow produced under stressed conditions. In boreholes with measurable ambient flow, numerical flow modeling was used to estimate transmissivity and the hydraulic head of each transmissive zone (Paillet, 1998). The difference between steady flows from a given transmissive zone into a borehole under ambient and pumping conditions is related to the transmissivity and water levels by

$$q^b{}_k - q^a{}_k = 2\pi T_k (w_a - w_b) \log_e(r_0/r),$$

where $q^a{}_k$ is the flow into borehole from zone k under pumping conditions, in length cubed per time,
$q^b{}_k$ is the flow into borehole from zone k under ambient conditions, in length cubed per time,
T_k is the transmissivity of zone k, in length squared per time,
w_a is the water level in the borehole under pumping conditions, in length,
w_b is the water level in the borehole under ambient conditions, in length,
r_0 is the zone radius, distance to the recharge boundary of the producing zone, in length, and
r is the radius of the borehole, in length.

The difference in flow is directly proportional to zone transmissivity because the ratio between the zone and borehole radius can be treated as a constant. The water level in an open borehole is the transmissivity-weighted average of the hydraulic head of the individual zones. The computer program of Paillet (2000), which simulates flow as a function of transmissivity and hydraulic head from a selected number of zones communicating along a borehole, was used to simulate the ambient and pumping flow profiles. Zone transmissivity and hydraulic-head estimates used in the model simulation were varied iteratively until qualitatively acceptable matches between flowmeter-measured and model-simulated profiles were reached.

RESULTS: INTEGRATED INTERPRETATION OF GEOPHYSICAL AND HYDRAULIC LOGS

Graphical representations of the conventional, OTV, radar reflection, and flowmeter logs discussed in this section are presented in appendixes 1-4. Copies of the digital files of all borehole-geophysical logs are maintained by the USGS at Storrs, Connecticut.

Foliation and Fractures

Integrated analysis of the OTV and conventional geophysical logs (Keys, 1990; Williams and Johnson, 2000; Williams and others, 2002) was used to identify foliation orientation and the location, distribution, and orientation of fractures within the 11 boreholes logged with the OTV at the Norwalk site (fig. 2).

The orientations of foliation and fractures observed in the boreholes are shown as poles to planes on lower-hemisphere equal-area stereo nets in figure 3. Although the orientation of foliation varies within individual boreholes and across the site, consistent with the presence of folding at both borehole and site-scales, some patterns can be detected. Poles to foliation cluster in three sets - one set strikes generally northwest and dips moderately to the southwest and moderately to steeply towards the northeast, a second steeply dipping set strikes north-northeast to northeast and dips southeast, and a third steeply dipping set strikes north-northeast to northeast and dips northwest (table 1). The poles to foliation planes, which plot in a girdle along the stereo net, suggest folding in the formation. The poles to fractures also cluster in three orientations, with most fractures striking north-northeast to northeast dipping east-southeast and west-northwest, and one set striking generally northwest dipping northeast.

There is a strong correlation between foliation and fracture orientation: most fractures strike sub-parallel to foliation, with dip directions similar to the foliation. Some of the fractures that strike parallel to foliation have high-angle dips that crosscut the foliation (fig. 3). The correlation between foliation and fracture orientation indicates that a structurally controlled fracture network is present at the Norwalk site.

The density of fracturing decreases with depth. Linear and exponential distributions fit to the data have similar coefficients of determination (R^2) of about 0.6. However, it is probably more reasonable to use the

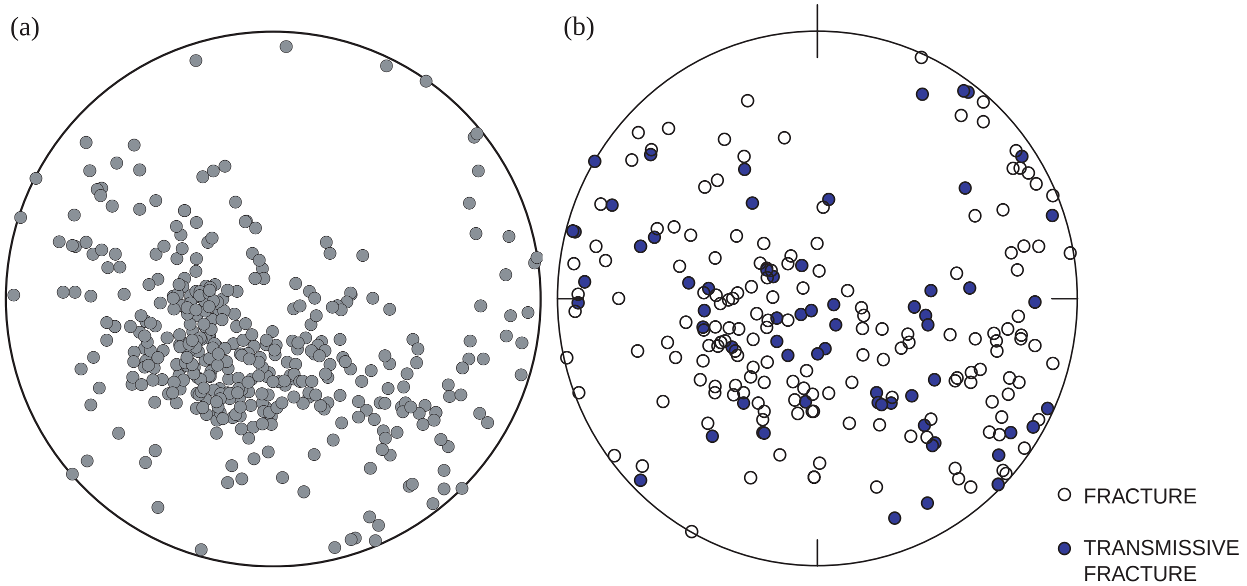

Figure 3. Equal-area stereonets of (a) foliation and (b) fractures, in 11 boreholes at the study area, Norwalk, Connecticut.

Table 1. Mean strikes and dips interpreted at the study area, Norwalk, Connecticut

[Strike is reported in degrees east of True North in “right-hand-rule” where direction of dip is to the right of strike; -, no data available]

	Strike, in degrees	Dip, in degrees	Length, in feet
Foliation	312	25	-
	214	39	-
Open fractures	209	45	-
	315	30	-
Transmissive fractures	215	41	-
	309	25	-
Radar reflectors	209	43	65
	305	35	65
Square array anisotropy	NE-SW[1]	-	-

[1] Because of limitations of this method, strike cannot be determined.

exponential distribution for extrapolation because the expected fracture density of the exponential distribution approaches zero with increased depth (Johnson, 1999).

A plot of fracture intensity or “interfracture spacing”, the distance between fractures observed in the boreholes, is shown in figure 4. The arithmetic average of the interfracture spacing is 5 ft, which corresponds to a mean fracture density of 0.2 fractures per foot. The frequency plot of fracture intensity shown in figure 4 was fit to exponential, power, and logarithmic functions. The best fit was obtained for the power law function, $y = 136.8x^{-1.697}$, where x is the distance between fractures and y is the number of fractures, similar to the findings of Johnson (1999) for fractures in metamorphic rocks at the USGS Mirror Lake fractured-rock

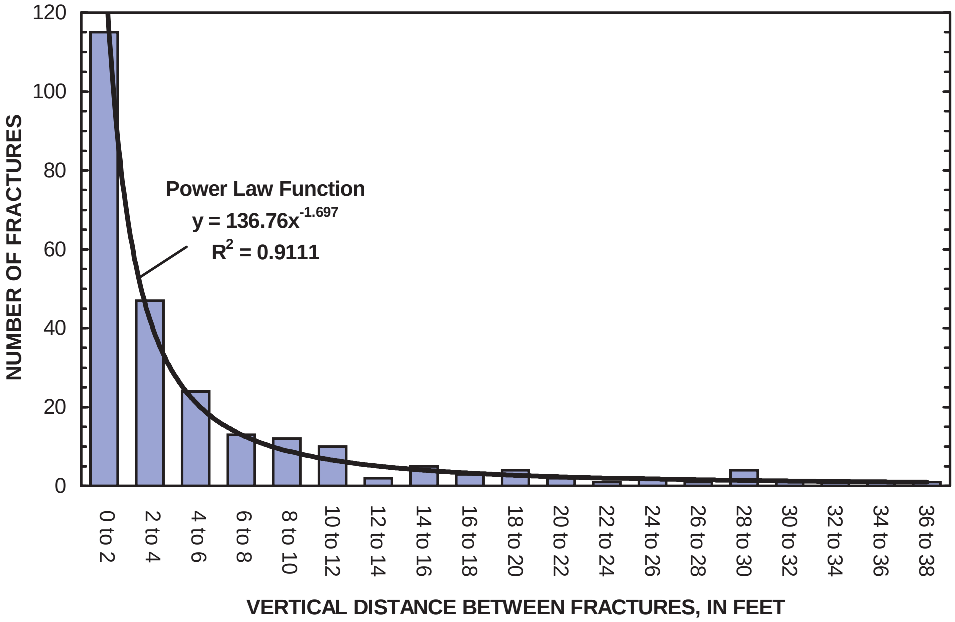

Figure 4. Fracture intensity for interpreted fractures in 11 boreholes at the study area, Norwalk, Connecticut.

field research site. The vertical distribution of fractures observed at the Norwalk site is consistent with a fracture network that contains highly fractured zones surrounded by a rock mass that is less fractured (Johnson, 1999).

Transmissive Fractures

Transmissive fractures were identified by integrated analysis of conventional (caliper, fluid temperature, and specific conductance), OTV, and flowmeter logs. Flowmeter logging was conducted with a HPFM and a specific conductance and temperature tool under ambient and low-rate pumping conditions. Transmissive zones interpreted in borehole MW-69 are shown adjacent to caliper, fluid, and flowmeter logs in figure 5.

The locations of the transmissive zones for 11 of the boreholes are shown in figure 6. A total of 33 transmissive zones were identified in these 11 boreholes. In most boreholes, 2 or 3 transmissive zones were detected by the HPFM. In one borehole, MW-46, the transmissive fractures were identified, but the magnitude of the transmissivity was not quantified. A lower hemisphere equal-area stereonet shows the orientation of all fractures in the transmissive zones for the site (fig. 3b). Individual stereonets that show the orientation of the transmissive fractures are plotted next to each borehole on the map in figure 2. Most of the transmissive fractures strike generally north-northeast to northeast, dipping to the southeast and northwest. About 20 percent of the north-northeast to northeast trending fractures are identified as transmissive compared to about 7 percent of the northwest striking fractures.

The fracture intensity for the transmissive fractures in 11 boreholes is shown in figure 7. The arithmetic average of the vertical interfracture spacings is 16.5 ft, which corresponds to an average transmissive fracture density of 0.06 per foot. As found for the open and oxidized fractures, a power law function best fits the observed distribution of transmissive fracture spacings, $y = 36.9x^{-1.912}$, with a coefficient of determination of 0.91. The vertical distribution of transmissive fractures observed at the Norwalk study area is consistent with a network of transmissive fractures that contains zones of transmissive fractures surrounded by a less transmissive rock mass (Johnson, 1999).

Identification of Large Fractures and Fracture Zones

Borehole-radar reflection logging was conducted using an electric-dipole transmitter and a magnetic-dipole directional receiver with nominal center frequencies, in air, of 60 MHz. Radial penetration of the radar was about 70 ft. A total of 114 reflectors were interpreted from 10 directional-radar reflection logs. Borehole-radar reflection logging was not conducted in MW-44 because of the short length of the borehole and the long length of the radar antennas. The orientations of the interpreted reflectors generally are consistent with the orientation of fractures at the site (table 1).

Radar-reflection methods image the dimension of a planar reflector that is parallel to the borehole. For this report, the length of the reflector parallel to the borehole was estimated using a straight-ray approximation that accounts for the source-receiver offset and the orientation of the reflector relative to the borehole. Assuming a uniform EM propagation velocity of about 0.4 ft/ns, the mean interpreted reflector length is 65 ft (table 1) with a standard deviation of 52 ft. The radar reflection log from MW-71 is shown in figure 8. Two steeply dipping reflectors are highlighted in the figure. Seventeen steeply dipping reflectors were identified in the reflection logs of three boreholes (MW-70, MW-71, and MW-72) close to the main building (fig. 2). These reflectors are vertically continuous for up to 100 ft, striking generally toward the southwest and northeast, with dips ranging from about 60º to 80º. Projections of the steeply dipping reflectors to land surface are shown in figure 2. The reflectors are interpreted as a north-northeast trending fracture zone. The boreholes do not penetrate most of the radar reflectors, so the hydraulic

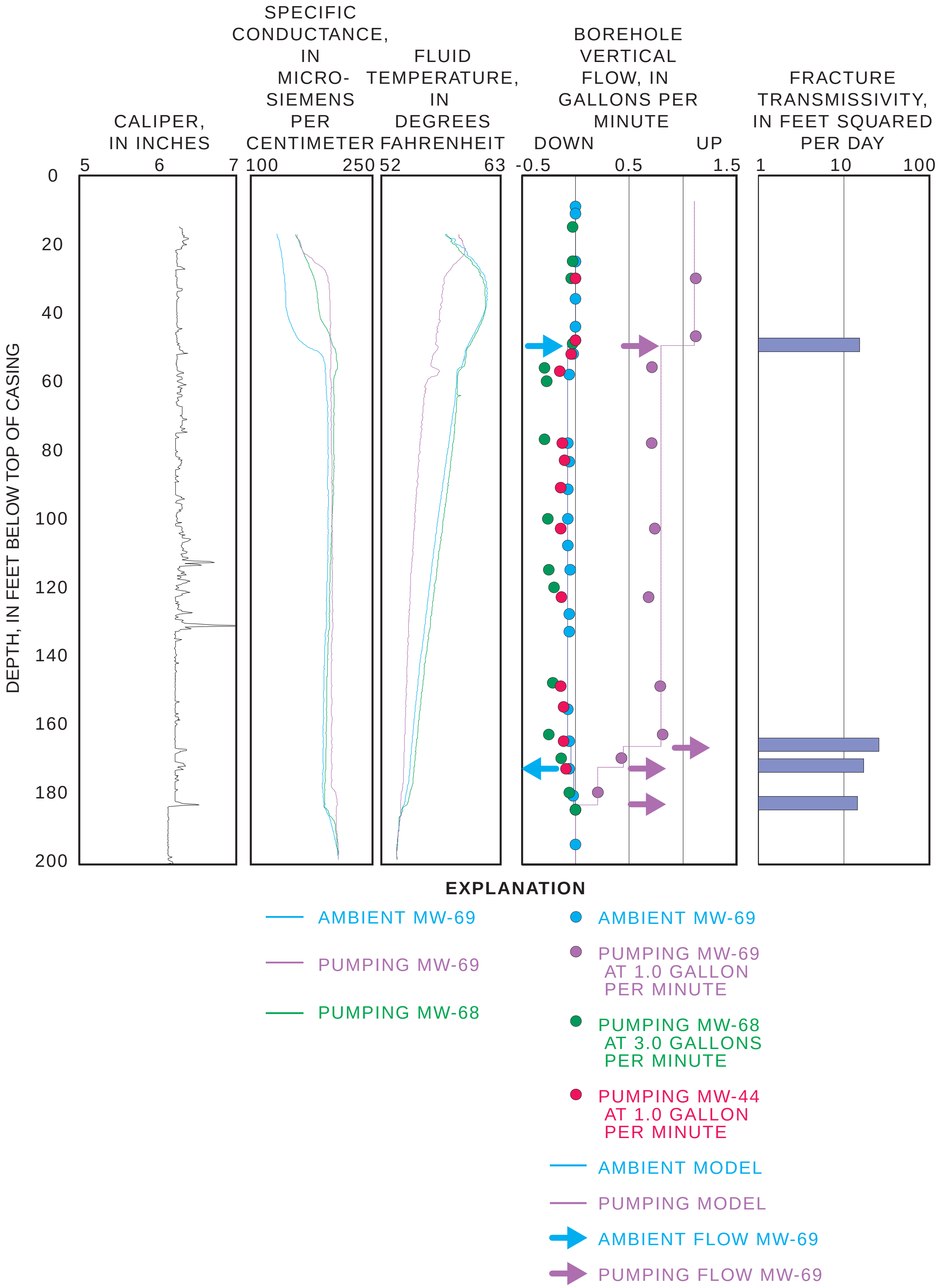

Figure 5. Caliper, specific conductance, and fluid temperature, under ambient and pumping conditions; modeled flow logs; and estimated fracture transmissivity for borehole MW-69, Norwalk, Connecticut.

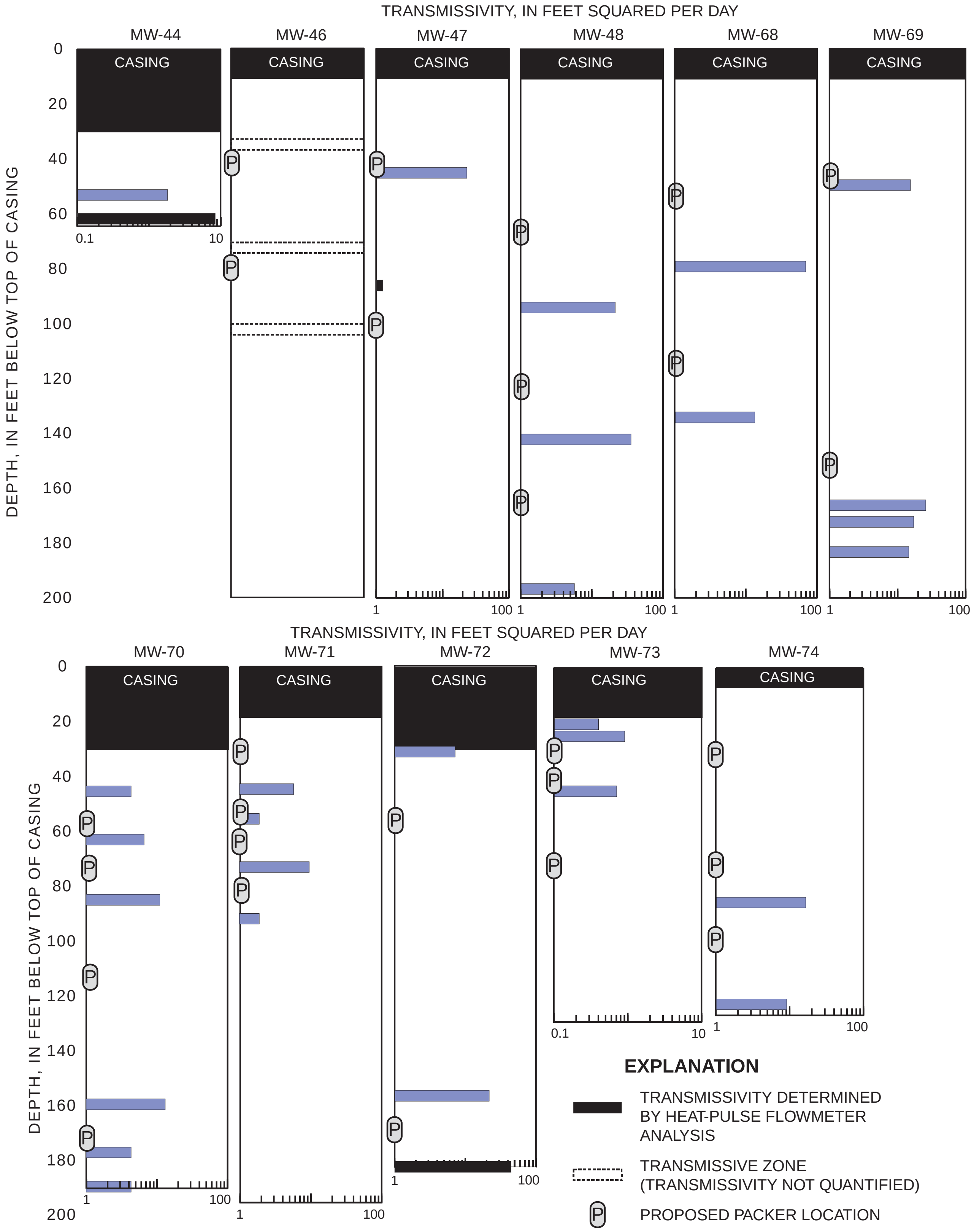

Figure 6. Locations of transmissive zones in several boreholes, with proposed locations of isolation packers in selected boreholes, Norwalk, Connecticut.

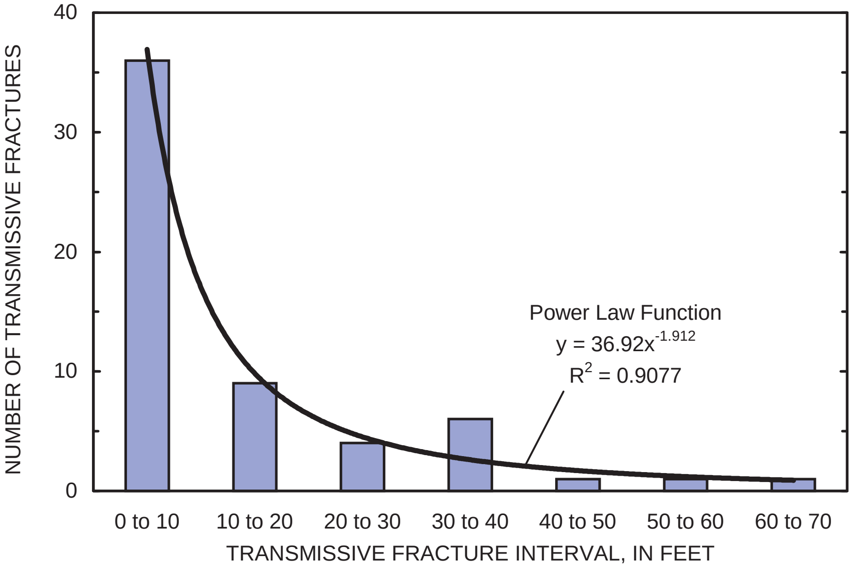

Figure 7. Fracture intensity of transmissive fractures in 11 boreholes at the study area, Norwalk, Connecticut.

characteristics of the reflectors are not known. However, one of the northeast striking, steeply southeast-dipping reflectors intersects borehole MW-72 at a major southeast-dipping fracture zone with an estimated transmissivity of 42 ft^2/d, suggesting that the reflector is a major hydraulic feature. The identification of northeast striking, steeply dipping, vertically continuous reflectors in the radar reflection logs, coupled with the observation that the steeply dipping reflector observed in the image logs of MW-72 is highly transmissive, indicates that vertically continuous, preferentially oriented, highly transmissive flow paths induced by large fractures or fracture zones that cross-cut lithologic structure and the network of structure-controlled fractures and penetrate to depths in excess of 100 ft are present at the Norwalk site.

Results of cross-hole radar tomography conducted between boreholes MW-73 and MW-74 near the suspected source areas are shown in figure 9. The tomography was conducted to delineate EM propagation velocity and attenuation anomalies that might provide insight into hydraulic connections between boreholes and to provide background data for difference tomography should an active remedial measure be attempted near the source zone. The tomographic surveys were conducted using electric-dipole antennas with nominal center frequencies (in air) of 100 MHz. A symmetric 0.8 by 0.8 ft transmitter-receiver geometry was used for the survey. Data were interpreted using a straight-ray conjugant-gradient inversion method (Ivansson, 1984). A zone of low EM velocity and high EM attenuation at depths less than 50 ft is seen in figure 9. This zone correlates with the locations of fractures recorded by the borehole-wall imagery logs. These cross-hole radar tomography results are specific to the plane between MW-73 and MW-74; they should not be extended beyond the immediate vicinity of the boreholes. However, the tomographic results do suggest radar-monitoring methods could be utilized in the source zone if a remedial measure that alters the EM properties of the fluids in the fractures is selected as a source-zone corrective action. For example air-sparging techniques could displace water in fractures, decreasing the attenuation of radar waves that traverse areas affected by remediation.

Azimuthal Resistivity Anisotropy

Azimuthal square-array dc-resistivity surveys were conducted at two sites (fig. 2).

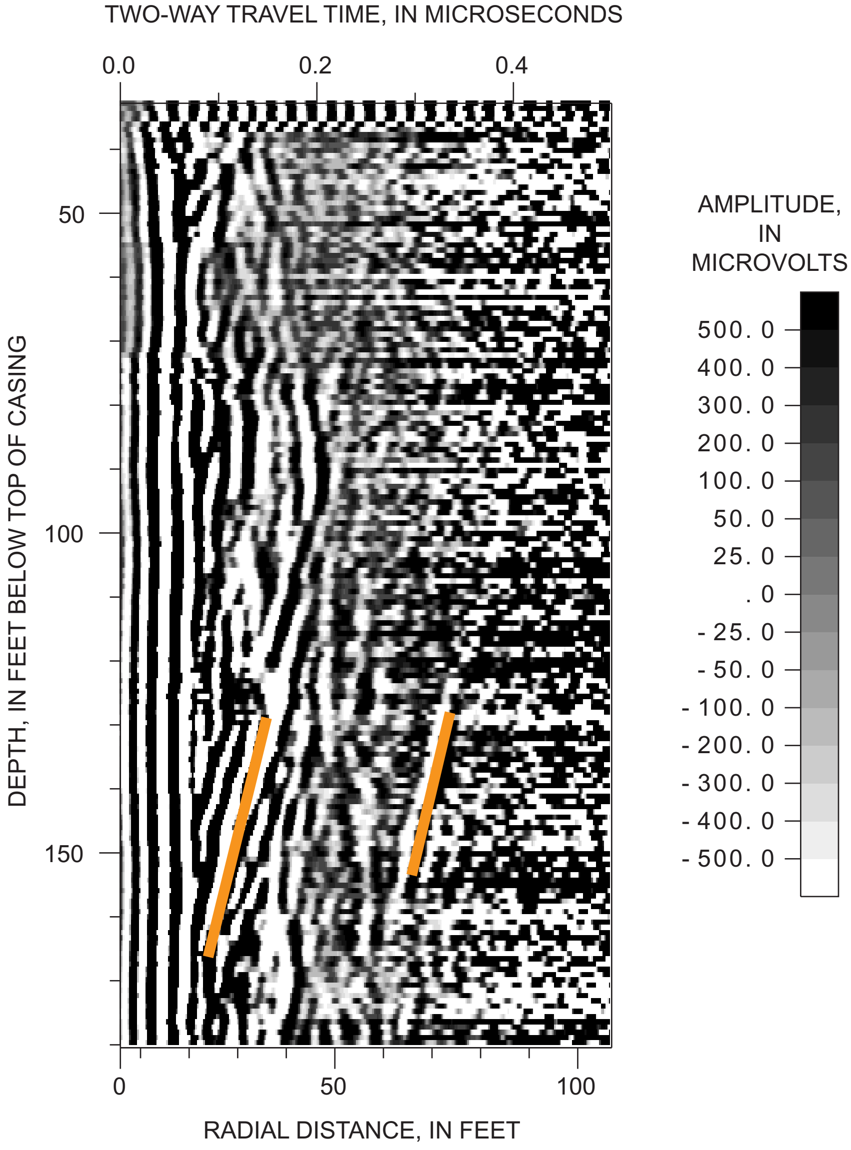

Figure 8. Sixty-megahertz directional borehole-radar reflection log from borehole MW-71, Norwalk, Connecticut. (The orange lines identify selected reflectors.)

The results from Square Array 1, located more than 1,000 ft from the general area of the boreholes, are shown in figure 10. The direction of apparent anisotropy interpreted from both azimuthal square array resistivity surveys is northeast (table 1), consistent with the direction of a dominant foliation and fracture orientation. The results of this surface-geophysical survey demonstrate that the general trends in fracture and foliation orientations observed in the boreholes can be measured from the surface and extrapolated beyond the location of the boreholes.

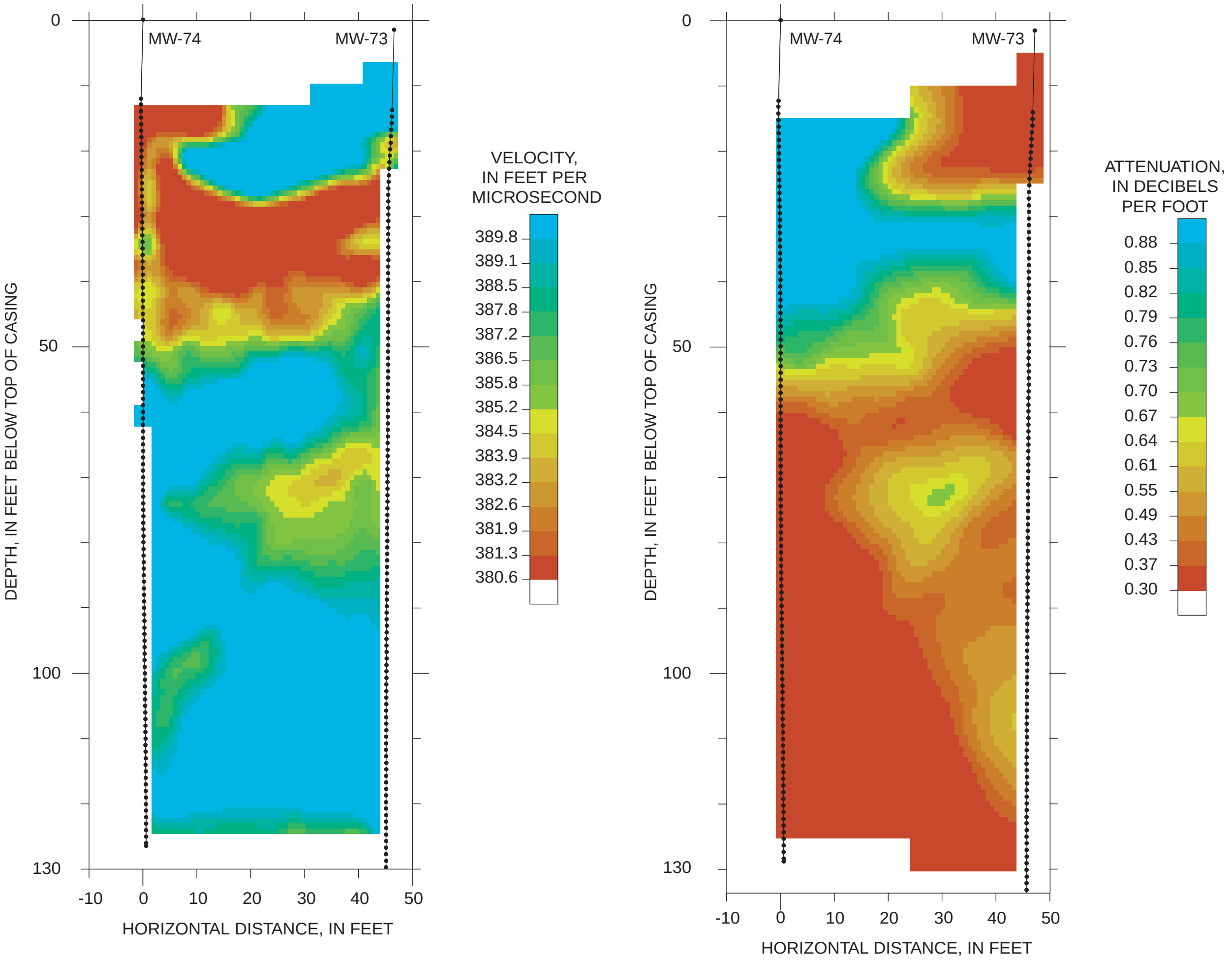

Figure 9. One hundred-megahertz cross-hole borehole radar tomography between boreholes MW-74 and MW-73, (left) velocity and (right) attenuation, Norwalk, Connecticut.

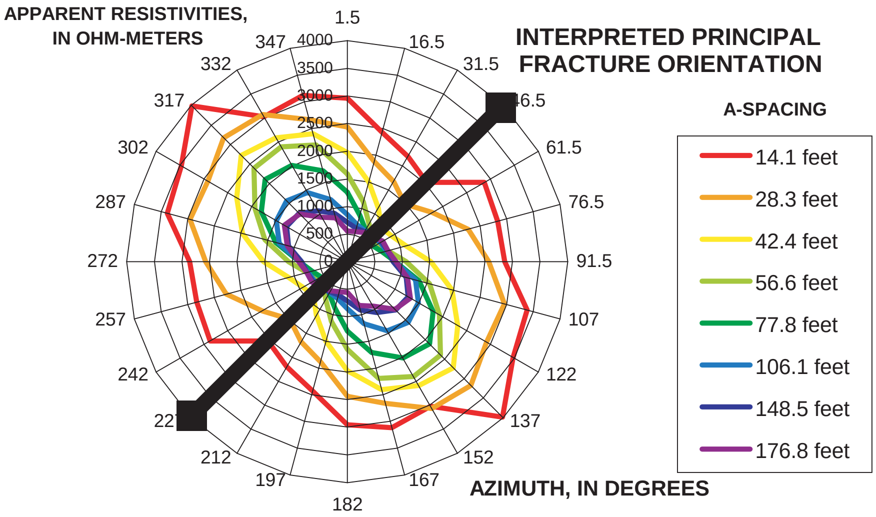

Figure 10. Results of azimuthal resistivity, Square Array 1, Norwalk, Connecticut. The A-spacing is the length of the side of the square.

RESULTS OF HYDRAULIC ANALYSES

This section presents the results of the hydraulic analysis of heat-pulse flowmeter data under ambient and pumping conditions to estimate open borehole specific capacity and transmissivity as well as the transmissivity and hydraulic head of individual transmissive fracture zones.

Hydraulic Head and Transmissivity for Individual Open Holes and Fracture Zones

Specific capacity and open-hole transmissivity were calculated from head and discharge data measurements made during flowmeter logging. By use of the algorithm of Bradbury and Rothschild (1985), which calculates transmissivity from specific-capacity data (table 2), the transmissivity estimates of the 10 open boreholes range from 2 to 86 ft^2/d with a median of 34 ft^2/d (borehole MW-46 was not included because of irregularities in the data).

In boreholes with no measurable ambient flow (MW-44, MW-47, MW-68, MW-71, and MW-73), the open-hole transmissivity was apportioned to individual transmissive zones according to the relative contribution of each zone to the total flow produced under pumping conditions. In boreholes with measurable ambient flow (MW-48, MW-69, MW-72, and MW-74), the flow-modeling method described by Paillet (2000) was used to estimate transmissivity and the hydraulic head of each transmissive zone. In borehole MW-70, upward flow was detected under ambient conditions but could not be assigned to specific zones so the open-hole transmissivity was apportioned based on the pumped flowmeter log.

For example, both measured and simulated ambient and pumping flow profiles and interpreted transmissivity for borehole MW-69 are shown in figure 5. In MW-69, there is ambient flow, with inflow at a depth of about 50 ft. Water flows down the hole and exits the borehole at two transmissive fractures below 165 ft. When MW-69 is pumped at a rate of 1.0 gal/min, there is upward flow with inflow from the upper and lower zones.

Transmissivity estimates for individual fracture zones range from 0.4 to 68 ft^2/d with a

Table 2. Transmissivity and cross-hole drawdown in selected boreholes at the study area, Norwalk, Connecticut
[Transmissivity determined from open hole tests, assumes storage coefficient equals 0.0005; -, no measured drawdown; distance (x) = 0 indicates water level in pumping borehole]

Pumped borehole	Pumping rate, in gallons per minute	Open hole transmissivity, in feet squared per day	Drawdown (s) and distance (x) from pumping well, in feet									
			MW-44		MW-68		MW-69		MW-70		MW-71	
			s	x	s	x	s	x	s	x	s	x
MW-44	1	11	15.4	0	0.29	560	0.38	467	-	-	-	-
MW-47	1	24	-	-	-	-	-	-	-	-	-	-
MW-48	1	70	-	-	-	-	-	-	-	-	-	-
MW-68	3	81	1.0	560	7.3	0	3.3	176	-	-	-	-
MW-68	1	81	1.0	560	2.4	0	1.0	176	-	-	-	-
MW-69	3	86	2.6	467	4.6	176	7.1	0	-	-	-	-
MW-69	1	73	1.3	467	1.3	176	2.5	0	-	-	-	-
MW-70	1	43	-	-	-	-	-	-	4.6	0	1.24	430
MW-71	.5	19	-	-	-	-	-	-	2.0	430	4.8	0
MW-72	1	70	-	-	-	-	-	-	-	-	-	-
MW-73	.25	2	-	-	-	-	-	-	-	-	-	-
MW-74	.5	25	-	-	-	-	-	-	-	-	-	-

median of 7 ft^2/d (table 3). Boreholes MW-48, MW-72, and MW-74 have upward hydraulic gradients with estimated relative head differences of less than 1 to about 10 ft between the lower and upper transmissive zones (table 4). A downward hydraulic gradient is present in MW-69 with an estimated relative head difference of about 1 ft.

Table 3. Transmissivity of transmissive zones in selected boreholes at the study area, Norwalk, Connecticut

Borehole	Depth, in feet	Transmissivity, in feet squared per day
MW-44	53.0	1.8
	61.6	8.4
MW-47	45.0	23
	86.0	1.2
MW-48	94.0	21
	142.0	35
	196.6	5.6
MW-68	79.0	68
	134.0	13
MW-69	49.4	15
	166.0	26
	172.0	17
	183.0	14
MW-70	45.5	4.3
	63.0	6.5
	85.0	11
	159.5	13
	177.0	4.3
	189.5	4.3
MW-71	44.6	5.7
	55.5	1.9
	73.0	9.5
	91.8	1.9
MW-72	31.0	7.0
	156.4	21
	182.3	42
MW-73	20.8	.4
	25.2	.9
	45.2	.7
MW-74	86.0	15
	123.0	10

Table 4. Estimated hydraulic-head difference of transmissive zones in selected boreholes at the study area, Norwalk, Connecticut

Borehole	Depth, in feet	Hydraulic-head difference, in feet
MW-48	94.0	-8.0[2]
	142.0	-7.0[2]
	182.3	.0
MW-69	49.4	1.0
	166.0	.0
	172.0	.0
	183.0	.0
MW-72	31.0	-1.8[2]
	156.4	.0
	182.3	.0
MW-74	86.0	-.75[2]
	123.0	.0

[2] Negative values indicate upward gradients

Hydraulic Connections

Open-hole water-level measurements collected during multiple-borehole, low-pumping rate hydraulic-stress tests were used to identify drawdown that might indicate the presence of hydraulic connections between boreholes. Connections were observed along a northeast-southwest trend between wells separated by distances of up to 560 ft (table 2 and fig. 2). The trend of the hydraulic connections is consistent with the general northeast-southwest strike of the bedrock, the interpreted fracture zone, and the observation that most of the transmissive fractures strike parallel to the bedrock foliation.

Connections between individual transmissive zones in MW-44, MW-68, and MW-69 were delineated by fluid and flowmeter logs collected during the multiple-borehole stress tests. The results of fluid and flowmeter logging conducted in borehole MW-69 when borehole MW-44 was pumped at 1.0 gal/min and when MW-68 was pumped at 3.0 gal/min are shown in figure 5. The increase in downward flow to the lower transmissive zones in borehole MW-69 during these tests suggests this zone is hydraulically connected to boreholes MW-44 and MW-68. Fluid and flowmeter logs in borehole MW-68 indicated that the lower transmissive zone provided a hydraulic connection to boreholes MW-44 and MW-69 when they were pumped.

Observation of hydraulic connections between open boreholes separated by up to hundreds of feet under low-flow pumping stresses provides a preliminary indication that fractures are well connected site-wide along northeast trends, and locally (over tens of feet) along northwest trends. Because the hydraulic connections were observed in open holes, additional information provided by discrete-zone pumping, tracer tests, or hydrograph analysis could be performed to ensure that the observed hydraulic connections are not the result of connections through the open holes. Observations of ambient and pumping-induced hydraulic gradients, estimations of open-hole specific capacity and zone-specific transmissivities, and the observation of preferentially oriented hydraulic connections provide indications of hydraulic results expected should moderate or high-yield pumping for testing, hydraulic containment, or treatment purposes be applied at the Norwalk site.

Discrete-Zone Monitoring

One of the goals of the geophysical investigation was to provide the information needed to design a discrete-zone monitoring (DZM) network in the fractured-bedrock aquifer. Properly designed DZM systems provide a way to monitor hydraulic head and sample the aquifer from specific zones, while preventing cross-contamination of the aquifer through open boreholes. In order to minimize cross-contamination, open boreholes temporarily were isolated using flexible borehole liners (Haeni and others, 2001) until the completion of testing and the installation of individual DZM systems. EM-induction, gamma, and borehole-radar logging were conducted with the liners in the boreholes. Borehole-wall imagery, fluid resistivity and temperature, and flowmeter logging required temporary removal of the liners. The results of borehole and flowmeter logging were used to determine potential locations of packers to isolate the transmissive zones (fig. 6).

SUMMARY AND CONCLUSIONS

The USGS conducted a geophysical and hydraulic investigation at the NSI site in Norwalk, Connecticut, where solvents have contaminated a fractured gneiss and schist aquifer. The investigation was conducted using a geophysical “toolbox” approach to fractured-bedrock characterization developed through studies at the USGS fractured-rock field research site, Mirror Lake, Grafton County, N.H. The purpose of this investigation was to characterize the lithology and structure of the site and to identify the orientation, distribution, and hydraulic characteristics of fractures and transmissive zones in the fractured-bedrock aquifer. This work supported ongoing efforts to develop a conceptual site model of ground-water flow and solute transport and to design a DZM and sampling network.

The suite of geophysical and hydraulic methods used for the investigation was selected to remotely measure bedrock fractures, lithologic structure, and transmissive zone hydraulic properties from the borehole to the field scale through the use of conventional logs, borehole imagery, directional radar reflection, cross-hole radar tomography, flowmeter, and azimuthal square-array resistivity methods.

Fracture and foliation orientations and distribution were determined by integrated interpretation of borehole-geophysical logs from 11 bedrock boreholes. Bedrock foliation at the site strikes northwest, dipping moderately northeast, and strikes north-northeast to northeast dipping both southeast and northwest. Most fractures are oriented parallel or sub-parallel to foliation. Some fractures that strike coincident with foliation have high-angle dips that crosscut the foliation. The correlation between foliation and fracture orientation indicates a structurally controlled fracture network at the Norwalk site. The density of fracturing decreases with depth, and the vertical distribution of fractures is consistent with a fracture network that contains highly fractured zones surrounded by a rock mass that is less fractured.

More than 100 planar reflectors were identified in the directional radar reflection logs. The interpreted orientations of the radar reflectors are consistent with the fracture and foliation orientations. The estimated average length of the reflectors is about 65 ft. Steeply dipping reflectors observed in the radar reflection data from three boreholes near the main building delineate a north-northeast trending feature interpreted as a fracture zone or fault. The identification of northeast striking, steeply dipping, vertically continuous reflectors in the radar reflection logs, coupled with the observation that the steeply dipping reflector in MW-72 is highly transmissive, indicates the presence of preferentially oriented, highly transmissive flow paths induced by large fractures or fracture zones that crosscut lithologic structure and penetrate to depths in excess of 100 ft.

Results of radar tomography conducted in two boreholes close to one of the suspected source zones indicate that a zone of low radar velocity and high attenuation exists above a depth of 50 ft, in the interval of the boreholes that contains a high density of fractures. The radar tomography results indicate that radar monitoring methods could be utilized if a remedial method that alters the contrast between bedrock and fracture EM properties is selected as a source-zone corrective action.

The axis of apparent electric anisotropy interpreted from azimuthal square-array resistivity surveys conducted at two locations on the site is oriented northeast-southwest, consistent with the orientation of transmissive fractures and one of the foliation directions. The surface azimuthal resistivity results demonstrate that general trends in fracture and foliation orientation observed in the boreholes can be measured from the surface and extrapolated beyond the location of the boreholes.

Flowmeter logging identified a total of 33 transmissive zones in 11 of the boreholes. The vertical separation of the transmissive zones typically is from 10 to 20 ft. Most of the fractures in the transmissive zones trend north-northeast to northeast, dipping both southeast and northwest; a smaller number of transmissive fractures have northwest strikes, dipping to the northeast. Drawdown measurements during flowmeter logging under pumping conditions identified hydraulic connections along a northeast-southwest trend between boreholes as far as 560 ft apart.

Open-hole and discrete-zone transmissivities were estimated from flowmeter data acquired under ambient and pumped conditions. The open-hole transmissivity of 10 of the boreholes ranges from 2 to 86 ft^2/d. The estimated transmissivity of the 31 transmissive zones ranges from 0.4 to 68 ft^2/d.

Synthesis of the results of the geophysical and hydraulic investigation indicates the fracture network at the Norwalk site is structurally controlled; most fractures are oriented parallel to foliation. Transmissive fractures strike preferentially to the northeast and southwest, but northwest striking transmissive fractures also are present. Power-law functions describe the vertical interfracture spacing of open and transmissive fractures. The power-law distribution suggests that the fracture network at the site contains transmissive zones consisting of closely spaced fractures surrounded by a less fractured and permeable rock mass. Northeast-trending, steeply dipping fracture zones that penetrate to depths as great as 100 ft could provide preferential pathways for horizontal and vertical fluid movement at the Norwalk site. Observations of ambient and pumping-induced hydraulic gradients, estimations of open-hole specific capacity and zone-specific transmissivities, and the observation of preferentially oriented hydraulic connections provide an indication of the magnitude of hydraulic response expected should moderate- or high-yield pumping for testing, hydraulic containment, or treatment purposes be used at the Norwalk site.

Although the results of this investigation provide information about bedrock lithology and structure, fracture location and orientation, and transmissive zone hydraulic properties, the characterization is incomplete. Specifically, the hydraulic parameters of the fractured-bedrock aquifer estimated from flowmeter logging are biased toward the properties of the most transmissive portions of the aquifer. Traditional packer testing would be required to characterize aquifer hydraulic properties below the measurement limit of the heat-pulse flowmeter. The areal extent of surface-geophysical surveys was limited and borehole logging was limited to existing boreholes and to a few boreholes installed during the investigation. Therefore, a sampling bias is present in the data because of the arbitrary location, orientation, and depth of the boreholes and survey locations. Statistical methods designed to correct biased data sets (Terzaghi, 1965; Martel, 1999) have not been applied to the geophysical and hydraulic data. The results of the investigation lack information that could be provided by other disciplines. For example, the correlation between foliation and fracture orientation suggests a geologic structural control on the fracture network at the site. High-resolution geologic mapping could provide insights into the hydrogeologic framework that might prove relevant to the development of the conceptual site model. Consistent with the hierarchal approach advocated by Shapiro and others (1999), the results of the geophysical and hydraulic investigation should be integrated with the most complete geologic, hydrologic, and geochemical information available to ensure the most robust conceptual site model possible.

Despite the shortcomings noted above, the hydrogeologic information provided by this investigation has served to identify the properties of the bedrock fracture system that, along with hydraulic gradients, likely contribute to the geometry of the observed contaminant plume. The information has allowed the precise placement of discrete zone ground-water monitoring systems to measure vertical hydraulic gradients and monitor ground water quality over time and to refine the conceptual site model.

Observation of rates of flow under ambient and stressed conditions and the orientation of transmissive fracture zones that control contaminant transport should provide information useful to site investigators and environmental regulators during the process of selecting and designing a site remedial remedy.

REFERENCES CITED

Bradbury, K.R., and Rothschild, E.R., 1985, A computerized technique for estimating the hydraulic conductivity of aquifers from specific-capacity data: Ground Water, v. 23, no. 2, p. 240-246.

Habberjam, G.M., and Watkins, G.E., 1967, The use of a square configuration in resistivity prospecting: Geophysical Prospecting, v. 15, p. 221-235.

Haeni, F.P., Lane, J.W., Jr., Williams, J.H., and Johnson, C.D., 2001, Use of a geophysical toolbox to characterize ground-water flow in fractured rock, *in* Fractured Rock 2001 Conference, Proceedings, Toronto, Ontario, March 26-28, 2001: Smithville Phase IV Bedrock Remediation Program, Smithville, Ontario, CD-ROM.

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

Ivansson, S., 1984, Crosshole investigations - tomography and its application to crosshole seismic measurements: Stockholm, Sweden, Stripa Project IR-84-08.

Johnson, C.D., 1999, Effects of lithology and fracture characteristics on hydraulic properties in crystalline rock -- Mirror Lake research site, Grafton County, New Hampshire, *in* Morganwalp, D.W., and Buxton, H.T., eds., U.S. Geological Survey Toxic Substances Hydrology Program-Proceedings of the Technical Meeting, Charleston, South Carolina, March 8-12, 1999: U.S. Geological Survey Water-Resources Investigations Report 99-4018C, v. 3, p. 795-802.

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

Kroll, R.L., 1977, The bedrock geology of the Norwalk North and Norwalk South quadrangles: State Geological and Natural History Survey of Connecticut, Quadrangle Report no. 34, 55 p.

Lane, J.W., Jr., Haeni, F.P., and Watson, W.M, 1995, Use of square-array direct-current resistivity method to detect fractures in crystalline bedrock in New Hampshire: Ground Water, v. 33, no. 3, p. 476-485.

Martel, S.J., 1999, Analysis of fracture orientation data from boreholes: Environmental and Engineering Geoscience, v. 5, no. 2, p. 213-233.

Olsson, O., Anderson, P., Carlsten, S., Falk, L., Niva, B., and Sandberg, E., 1992, Fracture characterization in crystalline rock by borehole-radar, *in* Pilon, J., ed., Ground penetrating radar: Geological Survey of Canada Paper 90-4, p. 139-150.

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. 997-1010.

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

Prudic, D.E., 1991, Estimates of hydraulic conductivity from aquifer-test analyses and specific-capacity data, Gulf Coast Regional Aquifers Systems, south-central United States: U.S. Geological Survey Water-Resources Investigations Report 90-4121, 38 p.

Shapiro, A.M., Hsieh, P.A., and Haeni, F.P., 1999, Integrating multidisciplinary investigations in the characterization of fractured rock, *in* Morganwalp, D.W., and Buxton, H.T., eds., U.S. Geological Survey Toxic Substances Hydrology Program-Proceedings of the Technical Meeting, Charleston, South Carolina, March 8-12, 1999: U.S. Geological Survey Water-Resources Investigations Report 99-4018C, v. 3, p. 669-680.

Terzaghi, R.D., 1965, Sources of error in joint surveys: Geotechnique, v. 15, p. 287-304.

Theis, C.V., Brown, R.H., and Meyer, R.R., 1963, Estimating the transmissibility of aquifers from specific capacity of wells, *in* Bentall, Ray, Methods of determining permeability, transmissibility and drawdown: U.S. Geological Survey Water-Supply Paper 1536-I, p. 331-341.

Williams, J.H., and Conger, R.W., 1990, Preliminary delineation of contaminated water-bearing fractures intersected by open-hole bedrock wells: Ground Water Monitoring Review, v. 10, no. 3, p. 118-126.

Williams, J.H., and Johnson, C.D., 2000, Borehole-wall imaging with acoustic and optical televiewers for fractured-bedrock aquifer investigations, *in* Proceedings of the Seventh International Symposium on Borehole Geophysics for Minerals, Geotechnical, and Groundwater Applications, October 24-26, 2000, Denver, Colorado: Minerals and Geotechnical Logging Society, p. 43-53.

Williams, J.H., Lane, J.W., Jr., Singha, Kamini, and Haeni, F.P., 2002, Application and integration of advanced geophysical logging methods in the characterization of a fractured sedimentary bedrock aquifer: U.S. Geological Survey Water-Resources Investigations Report 00-4083.

Williams, J.H., Lapham, W.W., and Barringer, T.H., 1993, Application of electromagnetic logging to contamination investigations in glacial sand and gravel aquifers: Ground Water Monitoring and Remediation Review, v. 13, no. 3, p. 129-138.