

Combined Use of Borehole Geophysics and Packers to Site Potable Wells in a Contaminated Area in Montville, Connecticut

Aaron Green, Connecticut Department of Environmental Protection; and John W. Lane, Jr., Carole D. Johnson, John H. Williams, Remo A. Mondazzi, and Peter K. Joesten, U.S. Geological Survey

Abstract

A leaking underground gasoline tank contaminated a crystalline bedrock aquifer in Montville, Connecticut, USA with MTBE and benzene. At the original residential bedrock supply wells, the median MTBE concentration was 165 micrograms per liter ($\mu\text{g/L}$), and the median benzene concentration was 320 $\mu\text{g/L}$. The maximum concentrations of MTBE and benzene were 4,300 $\mu\text{g/L}$ and 1,700 $\mu\text{g/L}$, respectively. Because of the unavailability of a public water supply and the long-term expense of point-of-use (on-site) treatment systems, the Connecticut Department of Environmental Protection Leaking Underground Storage Tank Program considered drilling replacement wells for water supply, if suitable drill sites could be located. Borehole geophysical methods were used as part of the investigation to find suitable drill sites. The U.S. Geological Survey performed borehole radar logging in three of the most contaminated wells. Other geophysical logs were run in two of the wells to enhance the hydrogeological characterizations. These data, combined with straddle-packer testing provided by a drilling contractor, formed the basis of a conceptual model used in the search for discrete fractures with better water quality than provided by an open-hole sample.

At Property A, a single transmissive fracture was identified at the bottom of the well. This well, although having historically lower gasoline concentrations than the other two wells, had persistent high iron bacteria fouling of the filtration system. By 2002, concentrations of MTBE and benzene had decreased to 59 and 3 $\mu\text{g/L}$, respectively, and the water was treatable except for the iron. Because no water-bearing fractures were encountered above the well bottom, an alternate well site was selected based on a set of vertical fractures observed in a nearby outcrop, rather than on the geophysical data. The new well, sited along the strike of these fractures, yielded 9 gallons per minute (gpm) but was found to be more contaminated than the original well. MTBE and benzene were detected at 224 and 7 $\mu\text{g/L}$, respectively. At Property B, the isolated fractures associated with four radar reflections contained MTBE in concentrations ranging from 460 to 680 $\mu\text{g/L}$, with concentration increasing with depth. A new well site was selected based upon topography and physical limitations of the property. A target drilling depth was selected to avoid encountering the most contaminated fracture, as projected from the radar data in the contaminated well. A new well, drilled to the target depth, yielded 2 gpm, which was sufficient for domestic supply. No contaminants were detected during 7 years of annual sampling. Over the next 2 years, MTBE was detected twice at 2 and 8 $\mu\text{g/L}$. At Property C, the isolated fractures associated with 12 radar reflections and acoustic televiwer images yielded MTBE concentrations ranging from 47 to 1,200 $\mu\text{g/L}$ and benzene concentrations from 6 to 1,000 $\mu\text{g/L}$, with concentrations generally increasing with depth. A new well site was selected based upon physical limitations of the site. A target drilling depth was chosen to avoid encountering the most contaminated fractures, as projected from the radar data in the contaminated well. A new well, drilled to the target depth, yielded 6 gpm. MTBE was detected at concentrations ranging from trace levels to 12 $\mu\text{g/L}$ for 6 years. Benzene was not detected.

These case histories suggest that the combined use of borehole geophysics and discrete-fracture sampling can, in some cases, be used to predict the locations of less contaminated or uncontaminated fractures, at distances of tens of feet from contaminated bedrock wells. This information may be used to improve the chances of successfully siting alternate potable water wells. Likewise, the same data and approach potentially could be used for targeting specific fractures for remediation.

Johnson, C.D., Lane, J.W., Jr., and Day-Lewis, F.D., 2004, Time-series monitoring in fractured-rock aquifers, in 2004 U.S. EPA/NGWA Fractured Rock Conference: State of the Science and Measuring Success in Remediation, September 13-15, 2004, Portland, Maine. Proceedings: National Ground Water Association, CD-ROM, p. 720-735.

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Introduction

Site History

A metamorphic bedrock aquifer in Montville, Connecticut, USA (fig. 1) was found to be contaminated with gasoline. In 1994 a series of subsurface investigations, conducted by the Connecticut Department of Environmental Protection (CTDEP) Leaking Underground Storage Tank (LUST) Program, identified the likely source of contamination as being a gasoline service station (Connecticut DEP, 1994 - 2004). Soil and shallow ground-water samples, collected using a truck-mounted Geoprobe^{®1} near the underground storage tank area, indicated high concentrations of the gasoline components benzene, toluene, ethylbenzene, xylenes, and methyl-tert butyl ether (MTBE), exceeding the State ground-water and soil remediation standards (RCSA, 1996) (table 1). In 1997, the gasoline tanks were removed and contaminated soil was excavated down to the bedrock surface at 9 feet (Connecticut DEP, 1994 - 2004), approximately the same depth as the water table.

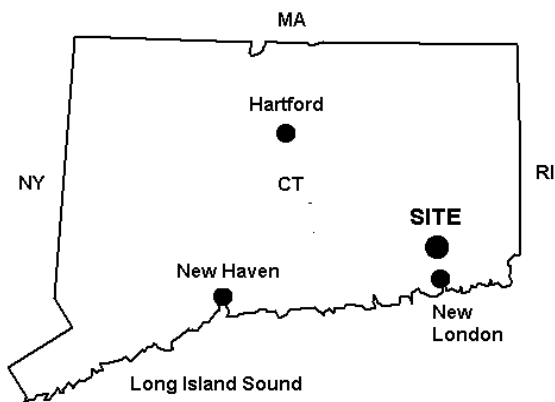


Figure 1. Site location, Montville, Connecticut.

MTBE and benzene were the predominant dissolved gasoline components detected in private bedrock supply wells (fig. 2). Beginning in 1992 MTBE, the most water-soluble of the chemicals, was detected in 17 wells and benzene was detected in 7 wells (Connecticut DEP, 1994 - 2004). Of the MTBE-impacted wells, seven had concentrations exceeding the State drinking water standard of 70 micrograms per liter ($\mu\text{g}/\text{L}$) (CTDPH, 2002). Benzene exceeded the State drinking water standard of 1 $\mu\text{g}/\text{L}$ at all seven wells. As a result, these properties were supplied with bottled water and/or point-of-use carbon filtration systems. The maximum MTBE and benzene concentrations were 4,300 $\mu\text{g}/\text{L}$ and 1,700 $\mu\text{g}/\text{L}$, respectively. A sheen of gasoline product as well as toluene, ethylbenzene, xylenes, and lesser gasoline components were found the well with the highest MTBE and benzene concentrations. Despite the 1997 on-site soil remediation, gasoline concentrations in the bedrock aquifer remain high, suggesting the presence of free-phase gasoline in fractures.

¹ The use of firm, trade, and brand names in this report is for identification purposes only and does not constitute the endorsement of the State of Connecticut or the U.S. Government.

Table 1. Shallow soil and ground-water quality near the leaking gasoline tank in Montville, Connecticut, compared to State of Connecticut remediation standards

[Bolded values indicate samples that exceed applicable remediation standard. $\mu\text{g}/\text{kg}$, micrograms per kilogram. $\mu\text{g}/\text{L}$, micrograms per liter.]

Contaminant	Soil		Ground water	
	Sample from 8 to 9 feet deep $\mu\text{g}/\text{kg}$	Remediation standard ¹ $\mu\text{g}/\text{kg}$	Sample, at water table $\mu\text{g}/\text{L}$	Remediation standard ² $\mu\text{g}/\text{L}$
Benzene	2,700	20	4,700	1
Toluene	3,000	20,000	15,000	1,000
Ethylbenzene	2,500	10,100	4,200	700
Xylenes	11,000	19,500	23,700	530
MTBE	130	2,000	1,800	100

¹Remediation standard is the Pollutant Mobility Criteria for ground-water areas classified as “GA”, which is a ground-water classification indicating it is presumed suitable for consumption without treatment.

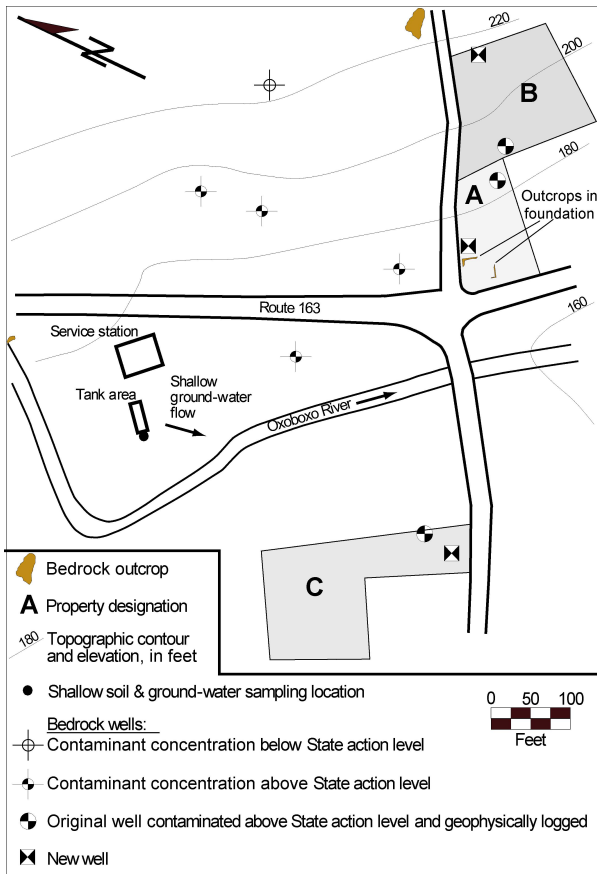
²Remediation standard is the Ground Water Protection Criteria for ground-water areas classified as GA.

Physical Setting

The site is located in an area of mixed residential, commercial, and industrial land use. The area in which this study is focused, the automotive service station and three residential properties, consists of about 5 acres. Domestic supply wells in the study area are 6 inches (in) in diameter and constructed with steel casing that generally extends 5 to 15 feet (ft) into bedrock and as open boreholes below the casing. The boreholes range in depth from 100 to 580 ft. Well yields, as reported by the drillers, range from 1 gallon per minute (gpm) to 20 gpm. Static water depths in the wells range from 15 to 50 ft below land surface. At the gasoline source area, the water table is likely to be within the bedrock seasonally. Some properties have low-yielding, uncontaminated dug wells for water supply. An extension of the public water supply into this area was recently planned for 2005. Properties along the main thoroughfare (Route 163) are connected to a public sewer, whereas those on the side roads are not. The CTDEP has classified the ground water of this area as “GA”, indicating that it is presumed suitable for consumption without treatment (Connecticut DEP, 1996).

The site lies within and on the eastern slope of the Oxoboxo River valley. The Oxoboxo River, which flows southeast and partially over bedrock, is a tributary of the Thames River. Just off the western edge of the site (fig. 2), the Oxoboxo River is dammed for industrial operations, and forms a pond with a year-round water level that is about 15 ft higher than that of the river. Land-surface elevations are between 160 and 220 ft above National Geodetic Vertical Datum of 1929. Surficial geologic materials were mapped as glacial stream deposits consisting of silt, sand, and gravel on the valley floor and as till up the valley slopes (Goldsmith, 1962). Goldsmith (1962) also mapped several bedrock exposures on the slope.

The site is located on the northern limb of the Montville Dome, which tectonically is within the Avalonian Terrane (Rogers, 1985). Goldsmith (1967) mapped the bedrock as consisting of two Hope Valley Alaskite Gneiss members of the Sterling Plutonic Suite and one member of the Plainfield Formation. The Sterling rocks are generally described as medium-grained gneissic granite and fine-grained, poorly foliated granite. The Plainfield member generally consists of schist and gneiss. These rocks strike northwest-southeast and dip about 60° to the northeast (Goldsmith, 1967).



Base from U.S. Geological Survey topographic quadrangle, Montville, Connecticut (1:24,000), 1983. National Geodetic Vertical Datum of 1929.

Figure 2. Location of properties, wells, bedrock outcrops, and contaminant sources in the study area in Montville, Connecticut.

Objectives

This study focuses on the three residential properties labeled A, B, and C on figure 2, which also shows the gasoline release area at the tank area at the service station. Because of frequent iron fouling, contaminant breakthrough, the long-term expense of the water treatment systems, the persistence of gasoline in the bedrock, and the prolonged uncertainty as to when public water would become available, the CTDEP pursued an alternate water supply solution. Borehole-geophysical logging was conducted in cooperation with the U.S. Geological Survey (USGS). A private well drilling company provided packers and drilling services.

The conceptual model for this site considers the fractured-rock aquifer to be a network of transmissive fractures and fracture zones consisting of interconnected permeable fractures surrounded by poorly connected fractures in an impermeable matrix. Thus, contamination originating near the land surface may affect some zones of the aquifer and any boreholes that are hydraulically connected to those zones, whereas other zones that are not in hydraulic connection remain unaffected.

With this conceptual model, the goal at each property was to gain sufficient information on the locations, orientations, and water quality of water-bearing fractures such that a new well could be drilled into pre-determined fractures containing better quality water than provided by each original well. If that were not possible, target-drilling depths would be selected with the intent of avoiding the fractures known to be contaminated. Topography, cultural features and small parcels of land constrained the available drilling sites to a minimum on each of the three properties. Therefore, casing length and completion depth were the only variables that could be controlled in the search for potable water in the bedrock.

Methods

Geophysical Logging

Bedrock wells at the three properties that were the focus of this project were geophysically logged and packer tested over a period of 7 years. Budgetary constraints and the availability of particular logging tools at different times resulted in a variety of methods used among the wells. The suite of geophysical logging tools used at properties A and C was more extensive than at B, enhancing the hydrogeologic characterizations of these wells. A summary of the geophysical tools used and their functions is provided in table 2.

Borehole radar was the only tool used at the first property studied, property B, and was the only tool common to all three wells. At the time borehole radar was first used for this project, it was relatively new to the USGS and was undergoing field tests. Because borehole radar methods image the bedrock surrounding the borehole, it was expected to be better suited to meet the project goals than the acoustic televiewer, an imaging tool previously used in a different CTDEP/USGS bedrock aquifer study (Paillet and others, 1992). The borehole radar tool consists of an electromagnetic transmitter and receiver in the same borehole, separated by a fixed distance (Singha and others, 2000). Borehole radar methods achieve greater radial signal penetration in electrically resistive materials, because electromagnetic waves are attenuated by conductive materials. The radar logging was performed using 60 megahertz (MHz) directional antennas and dipole configurations with readings collected down the borehole at 0.82-ft increments (0.25 meter).

The heat-pulse flowmeter (HPFM) measures the vertical direction and rate of water flow in a borehole. HPFM operates by generating a heated pulse of water and detecting the pulse after having flowed upward or downward from the point of origin (Hess and Paillet, 1990). The HPFM was run under ambient and pumping conditions. The ambient measurements were performed to check for non-induced vertical flow, resulting from differential heads within the well. Drawdown was achieved during pumping in an effort to release water from permeable, but otherwise nonflowing fractures for the purpose of detecting their locations.

Table 2. Geophysical tools used in bedrock wells in Montville, Connecticut

[X indicates a geophysical log was collected in the original wells at the site.]

Tool	Property			Tool function	Reference
	A	B	C		
Gamma	x		x	Provides information on lithology by measuring natural gamma emitted from bedrock.	Keys, 1990
Caliper	x		x	Measures borehole diameter using three mechanical arms.	Keys, 1990
Temperature	x		x	Measures water temperature profile in well to help identify permeable zones.	Keys, 1990
Fluid Conductivity	x		x	Measures electrical conductivity of water in well to help identify permeable zones.	Keys, 1990
Acoustic Televiewer (ATV)	x		x	Measures acoustic attenuation of borehole wall, providing images of geologic features.	Williams and Johnson, 2004
Optical Televiewer (OTV)	x		x	Provides a color, oriented optical image of borehole wall allowing for lithologic and structural interpretations.	Williams and Johnson, 2004
Borehole Radar	x	x	x	Measures electromagnetic wave attenuation beyond the borehole, providing structural information on planar features.	Lane and others, 1994 Olsson and others, 1992
Heat-Pulse Flowmeter (HPFM)	x		x	Determines the vertical flow, and transmissive fracture locations, by tracking heated pulses of water at discrete depths.	Hess and Paillet, 1990

Discrete-Zone Testing

After interpretation of the logging data, an inflatable packer system was lowered to the depths of interest to isolate known or suspected water-bearing fractures in the borehole. The packers were constructed of 2-ft-long inflatable rubber bladders connected by 2-in-diameter perforated pipe of variable length. The unit was lowered on sections of threaded, non-perforated pipe. Inflation lines extended to the surface where a tank of nitrogen provided the inflation gas. Hydraulic heads within the isolated zones were monitored, and water samples were collected using a bailer and/or submersible pump. On the trip downhole, the packers were positioned to straddle the targeted intervals and were inflated. The hydraulic head within each interval was monitored with an electronic water-level indicator until equilibrium or near-equilibrium conditions were reached between the packers. On the return trip up the well, the same zones were isolated for water sampling. The final head in the zone and the purge volumes were reported. Packers were used at all three properties. All water samples were analyzed for volatile organic compounds (VOCs) using gas chromatography.

Outcrop Evaluations

Location, strike, and dip of fractures were measured at outcrop faces, some of which were part of the foundation of a building (fig. 2). This method was used only at Property A.

New Well Drilling

New wells were drilled at each property using air rotary drilling methods. Ground-water samples were collected as water-bearing zones were encountered, and after completion of the wells.

Data Collection

Property A is a residential property of concern containing a four-unit apartment building. The original well is 258 ft deep. Although MTBE was the predominant contaminant, iron bacteria, which caused frequent fouling of the water treatment system, also was a concern. Evidence of MTBE concentrations with time is shown on figure 3a.

During logging and packer testing, the building was connected to a temporary potable water source, supplied by a tanker truck. The geophysical logging methods identified in table 2 were used to characterize the fractured rock aquifer. After interpretation of the geophysical data, one interval was selected for packer testing. The HPFM was run under ambient and low-rate (about 0.5 gpm) pumping conditions, achieving about 9 ft of drawdown.

An additional method of gathering fracture data for locating a new well was to map the location and orientation of fractures in nearby outcrops. Fractures appearing on bedrock outcrops forming a portion of the foundation wall of the apartment building (fig. 2) were projected to a new well location. A new well was drilled and sampled.

Property B is a residential property containing a single-family home. The original well is 250 ft deep. MTBE and benzene were the contaminants of concern, as indicated by the concentrations shown on figure 3b. Additionally, unpleasant gasoline odors were present in the home while the water was in use.

Data gathered from the radar survey and the well completion report were evaluated and used to select packer-testing intervals. It is noteworthy that the well completion report, submitted to the State after the well was drilled in 1977, was detailed and accurate concerning the depths at which the driller encountered “water bearing seams.”

The dual, inflatable packers were pre-set with an intake interval of 6.2 ft. Hydraulic head was monitored in the discretely isolated zones, and samples were collected with a bailer and submersible pump. Variable amounts of water were purged prior to sampling, depending upon the productivity of the zone.

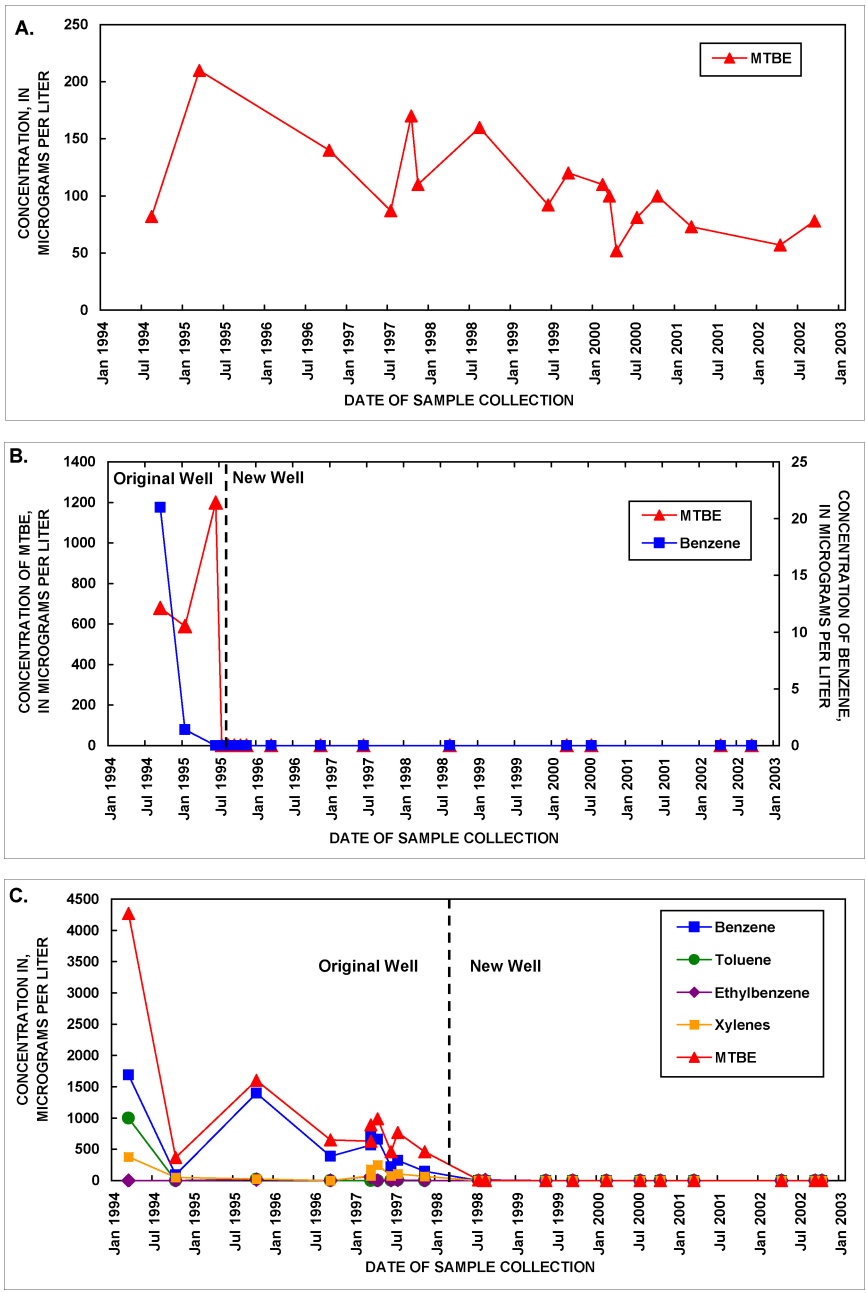


Figure 3. Contaminant concentrations in bedrock wells in Montville, Connecticut.

Due to topographic and physical constraints on this property, such as buildings, a driveway, and a septic field, only a single drill site for a replacement well was available. Therefore, casing length and completion depth for the new well were the only variables that could be controlled in an effort to tap into uncontaminated, or less contaminated, water-bearing fractures. Assuming the radar reflectors were planar and continuous, the elevations at which they would pass through the drill site were predicted using Equation 1:

$$E_2 = E_1 + [(D) (\tan \theta)] \tag{1}$$

where E_2 is the projected reflector elevation at the new drill site; E_1 is the reflector elevation at the original well; D is the horizontal distance between the original well and the drill site (perpendicular to the strike of the reflector); and θ is the dip angle (fig. 4). The quantity ($D \tan\theta$) is defined as negative when the projection is on the down-dip side of the well and positive on the up-dip side of the well. Upon evaluating the water-quality results in context of the anticipated reflector elevations at the drill site, a target drilling elevation was selected, allowing for a 10-ft vertical buffer zone.

Property C is a residential property containing a single-family home supplied by a 300-ft-deep well. Concentrations of benzene, toluene, ethylbenzene, xylenes and MTBE, all detected in this well, are shown on figure 3c. The water also had a gasoline sheen. The geophysical tools used and their functions are listed in table 2.

The HPFM was run under ambient and pumping conditions with about 11 ft of drawdown achieved during pumping. Based upon the results of the geophysical logging, 12 intervals were selected for packer testing. The dual, inflatable packers were pre-set with an intake interval of 9 ft and lowered down the well. Hydraulic head was monitored in the discretely isolated zones, and samples were collected from the isolated zones using a submersible pump. Variable amounts of water were purged prior to sampling, depending on the productivity of the zones.

Results

Property A

Under ambient conditions, the HPFM data, collected at 18 depths, indicated no flow. Under pumping conditions, the HPFM data, collected at 20 depths, showed that all of the water was originating from the bottom of the well from fractures at 248 to 250 ft below the top of casing. This fracture zone was observed in the caliper, ATV, OTV, and radar logs. As expected, this zone, providing all of the water to the well, was contaminated with MTBE and benzene at concentrations of 59 and 3 $\mu\text{g/L}$, respectively. Similar, single-fracture bedrock wells have been identified, including one described by Paillet and others (1992) in the metamorphic rock of eastern Connecticut. Seventeen radar reflectors were found to intersect or nearly intersect the well (table 3)

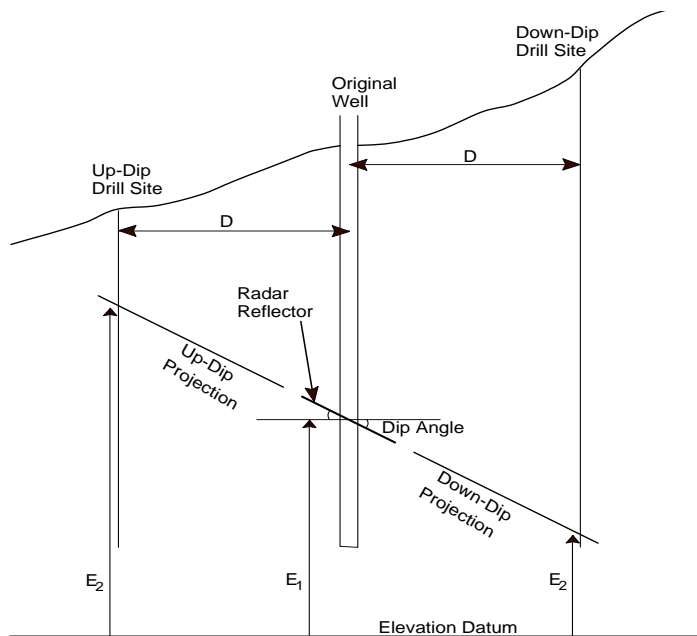


Figure 4. Hypothetical radar reflector projected to up-dip and down-dip new drill sites.

Table 3. Summary of borehole radar reflector data from original well at Property A in Montville, Connecticut
 [-- Indicates strike could not be determined.]

Reflector	Depth below top of casing (ft)	Elevation	Strike ¹	Dip
a	59.4	120.1	5	57
b	68.9	110.6	325	47
c	101.1	78.4	313	64
d	161.8	17.7	--	65
e	178.8	0.7	312	60
f	200.1	-20.6	193	70
g	204.7	-25.2	197	72
h	214.9	-35.4	255	78
i	222.8	-43.3	--	73
j	227.0	-47.5	204	66
k	234.9	-55.4	295	58
l	235.2	-55.7	95	49
m	238.5	-59.0	--	64
n	239.8	-60.3	15	47
o	245.1	-65.6	335	73
p	246.4	-66.9	208	64
q	258.5	-79.0	75	83

¹Strike and dip are presented in the right-hand rule where the strike is in degrees east of north and the dip direction is to the right of the strike.

Since no water-bearing zones were identified above the elevation of the contaminated zone, an alternate approach was used. The exposed fractures within the building basement, striking about 12° east of north and dipping near vertical, were traced along strike to a suitable new drill site. Being densely spaced and frequently wet in appearance (6 ft below the ground surface), these fractures provided the best opportunity to find ground water in a zone other than the contaminated zone confirmed to exist at the bottom of the original well.

The new well intersected ground water on top of the bedrock surface (10 ft deep). This water was sampled and found to contain no gasoline components. After removal of the drill rods, the borehole was checked for water at depths of 68 and 109 ft, but no ground water was found. Drilling continued to 115 ft, where water was found to contain MTBE at a concentration of 214 µg/L. Drilling continued to 149 ft, where another water sample had concentrations of MTBE and benzene at 224 and 7 µg/L, respectively. The well was completed at this depth and yielded 9 gpm. Six weeks after completion, the well was sampled after purging, and found to be contaminated with MTBE and benzene at 360 and 140 µg/L, respectively. The new well was not used as an alternate water supply.

Property B

Borehole radar reflector data and well completion data are summarized in table 4. Since no other geophysical tools were used in this well, it was fortuitous that the original well completion report, reflecting conditions encountered by the driller in 1977, was available. This report contained substantially more hydrologic data than commonly encountered in these reports, and provided complimentary information to the radar data.

Eight reflectors, designated “a” through “h” on table 4, were identified. Because of interference, noise, or poor quality of data in this zone, it was only possible to resolve the dip direction of two low-angle reflectors, “c” and “d,” into two possible directions. Thus, these reflectors were assigned duplicate reflectors, “c-1” and “d-1”, respectively, having opposite dip directions. Three “water bearing seams,” as reported on the driller’s 1977 well

completion report, closely match reflectors “c”, “g,” and “h”. Identified by the driller at 47, 145, and 230 ft, these fractures are only 2.2, 1.1, and 1.2 ft deeper than the corresponding reflectors.

Due to their proximity to each other, reflectors “a” and “b” were isolated within the same packer interval and designated as packer zone “a/b” (table 5). The remaining reflectors were designated and tested as individual packer zones. Of the seven zones, only “a/b” was dry. Final hydraulic heads were recorded in the remaining six zones. Although they were not all static heads, they provide an indication of the likely direction of vertical gradients. The hydraulic heads in the upper five packer zones increased with depth, suggesting potential for upward flow. The sixth, and deepest zone, had a head almost 4 ft higher than the next nearest head, indicative of a potential for flow.

Table 4. Summary of borehole radar reflector data compared to water-bearing zones identified in the Well Completion Report for the original well on Property B, Montville, Connecticut

[All distances are in feet. Bold data (in blue) indicate reflectors consistent with location of fractures in the well completion report.]

Reflector	Depth below		Elevation ¹	Strike ²	Dip	Depth of water-bearing zone ³
	Top of casing	Land surface				
a	17.8	16.9	164.9	296	23	
b	19.1	18.2	163.6	286	62	
c	45.6	44.8	137.0	116	5	47
c-1 ⁴	45.6	44.8	137.0	296	5	
d	51.9	51.0	130.8	116	33	
d-1 ⁴	51.9	51.0	130.8	296	33	
e	84.4	83.5	98.3	296	67	
f	102.4	101.5	80.3	286	61	
g	144.7	143.9	38.0	296	62	145
h	229.7	228.8	-47.0	116	49	230

¹ Feet above National Geodetic Vertical Datum of 1929.

² Strikes and dips are presented using the right-hand rule where the strike is in degrees east of north, and the dip direction is to the right of the strike.

³ Depth of “water bearing seams” identified on the 1977 Well Completion Report on file with the CTDEP in feet below land surface.

⁴ Reflectors c-1 and d-1 are duplicates of reflectors c and d, respectively, which account for two possible strike directions.

Table 5. Packer test results from original well on Property B in Montville, Connecticut

[The whole-well results are included for comparison. Test zones that correspond to water-bearing zones in the well completion report are shown in bold (and in blue). All distances are in feet. “Dry” indicates the zone yielded no water. ND indicates none detected. NA indicates not applicable. NS indicates not sampled due to insufficient yield. NP indicates well not purged prior to collection of whole-well sample.]

Designation ¹	Packer test zones			Concentration (micrograms per liter)	
	Depth to center (feet from casing top)	Water purge volume (gallons)	Elevation of final head ²	MTBE	Benzene
a/b ³	18.4	dry	dry	dry	dry
c	45.6	4.0	152.72	460	ND
d	51.9	NS	152.86	NS	NS
e	84.4	4.0	154.40	480	ND
f	102.4	NS	154.40	NS	NS
g	144.7	5.5	153.97	620	ND
h	229.7	26.0	158.25	680	ND
Whole well	NA	NP	NA	1,200	ND

¹ Corresponds to designation of radar reflectors.

² Feet above National Geodetic Vertical Datum of 1929. Not necessarily static head conditions.

³ Zones were combined.

As expected from the well completion report, zones “c”, “g” and “h” produced sufficient quantities of water for purging and sampling. Zone “e” also was purged and sampled. Zones “d” and “f” provided insufficient water for sampling. MTBE concentrations increased with depth from 460 to 680 µg/L in the four sampled zones. Benzene was not detected. Final recorded heads and contaminant concentrations are listed in table 5.

Orientations of the sampled zones were projected along the dip azimuths using Equation 1. The predicted elevations at which the reflectors would pass beneath the new drill site were converted to depths below ground surface. Of the four packer zones that were contaminated, “e” and “g” projected the deepest (278 and 305 ft below ground surface, respectively). The least contaminated zone, “c”, was essentially horizontal and projected to a depth of 64 ft beneath the drill site. The most contaminated zone, “h”, projected to a depth of 161 ft.

Based upon the contaminated zone projections to the new drill site, we assumed that water containing low contaminant concentrations would likely be found at about 64 ft and that water containing the highest contaminant concentrations would be found at about 161 ft. Therefore, it was decided to (1) drill through the 64-ft-deep water-bearing zone (least contaminated fracture) with the expectation that the contaminated water would be adequately diluted by upslope recharge, and (2) stop drilling above the 161-ft-deep, highly contaminated, fracture projection. A target drilling depth of 151 ft was selected, thereby avoiding the projection of fracture “h” by 10 ft.

The well was drilled to 151 ft and yielded 2 gpm. The driller identified water-bearing zones at the following depths: 40, 65, 86, 113, 127, and 149 ft. Ground-water samples were collected during drilling at four of these depths (65, 86, 113, and 149 ft). No VOCs were detected. Additionally, a whole-well sample collected 8 days after purging, did not contain any VOC contaminants. During the monitoring period, covering the next 5 years, the well remained uncontaminated.

Property C

Selected borehole geophysical logs are shown for the original well on Property C (fig. 5). In general, the bedrock was identified as felsic igneous rock to a depth of about 175 ft and schist to the bottom of the well. The reflected borehole radar signal is stronger in the granite than in the schist, because of the differences in electrical conductivities between the two rock types (fig. 6). Fifteen radar reflectors were identified as intercepting the borehole (fig. 6 and table 6). The HPFM detected no ambient flow. Under pumping conditions, upward flow was detected throughout the borehole (at 10 measurement stations) above a depth of about 190 ft. The inflow was attributed to fractures at about 70, 135, and 197 ft below the top of casing (fig. 5). From a depth of 198 ft to the well bottom (300 ft), no flow was detected at four stations. Also, the fluid conductivity and temperature logs indicate a change in the fluid column at a depth of about 200 ft below the top of casing, supporting the flowmeter interpretation.

As a result of the combined analysis of ATV, radar, and HPFM data, 12 zones, designated “a” through “l” were selected for packer-testing (table 7). Relatively uniform concentrations of MTBE (47 to 79 µg/L) and benzene (6 to 12 µg/L) were found to a depth of about 133 ft. At and below a depth of about 163 ft below top of casing (the next deeper interval), the concentrations increased significantly.

The upper six, less contaminated, zones (“b” through “g”) projected to depths of 144 ft below top of casing and shallower at the new drill site. The remaining five deeper, more contaminated zones (“h” through “l”) projected to depths of 147 ft and deeper at the new drill site. The new well was drilled to 120 ft, thereby avoiding fracture “h” by 27 ft. Packer testing in the original well showed that fracture “h” contained MTBE and benzene concentrations of 470 and 330 µg/L, respectively. The new well yielded 6 gpm at a depth of 120 ft. Therefore, it was not necessary to continue downward toward 147 ft, the predicted depth of contamination, and risk intersecting fracture “h”. The driller identified water-bearing zones at the following depths: 29, 35, 38, 44, and 76 ft. Ground-water samples were collected during drilling at 29, 50, 90, and 110 ft. No VOC’s were detected. A whole-well sample collected 11 days after purging, contained MTBE at a concentration of 12 µg/L, but contained no benzene. During the monitoring period, covering the next 6 years, MTBE was detected once at a concentration of 1 µg/L and benzene was not detected (fig. 3c).

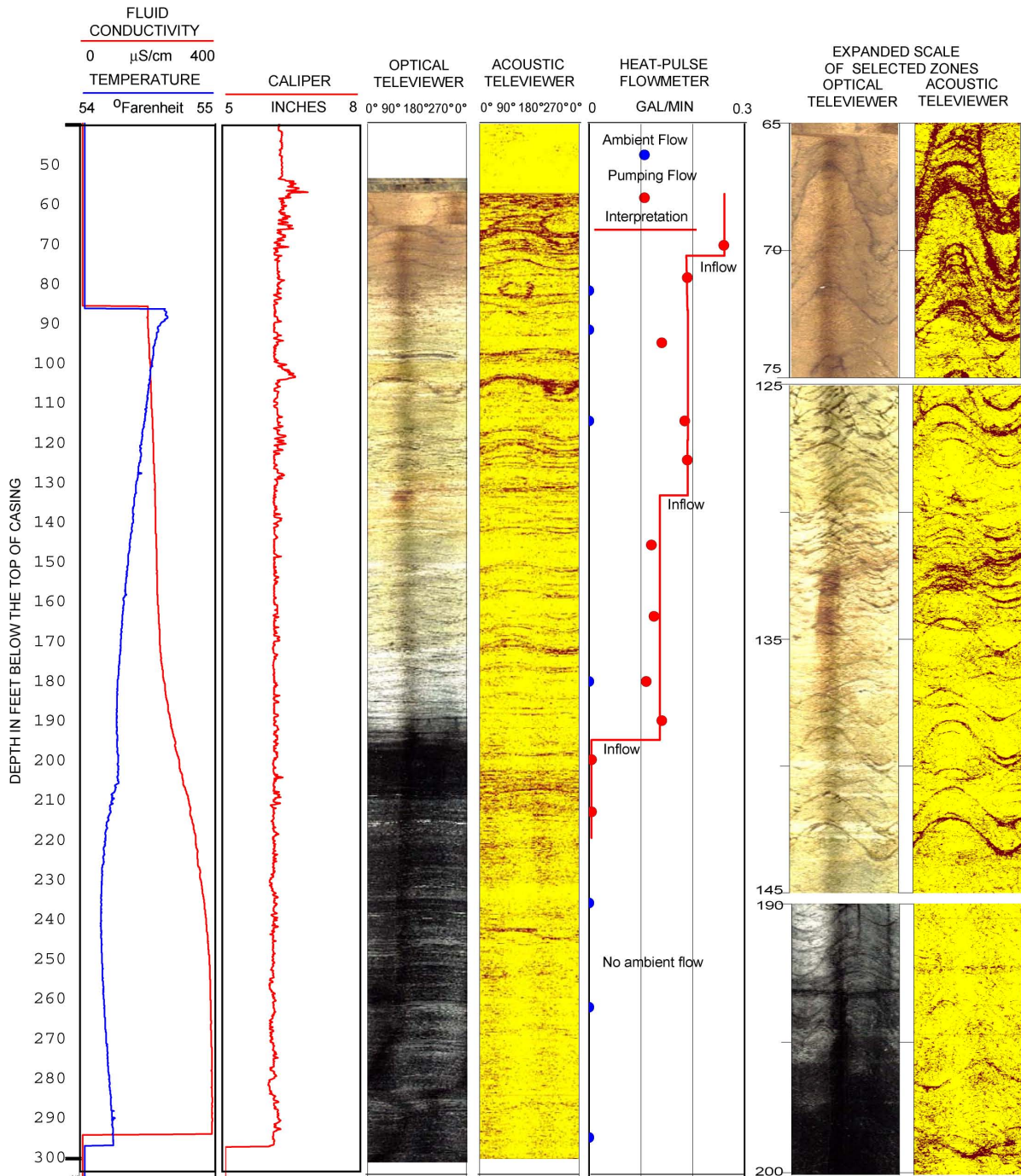


Figure 5. Geophysical logs from the original well on Property C in Montville, Connecticut.

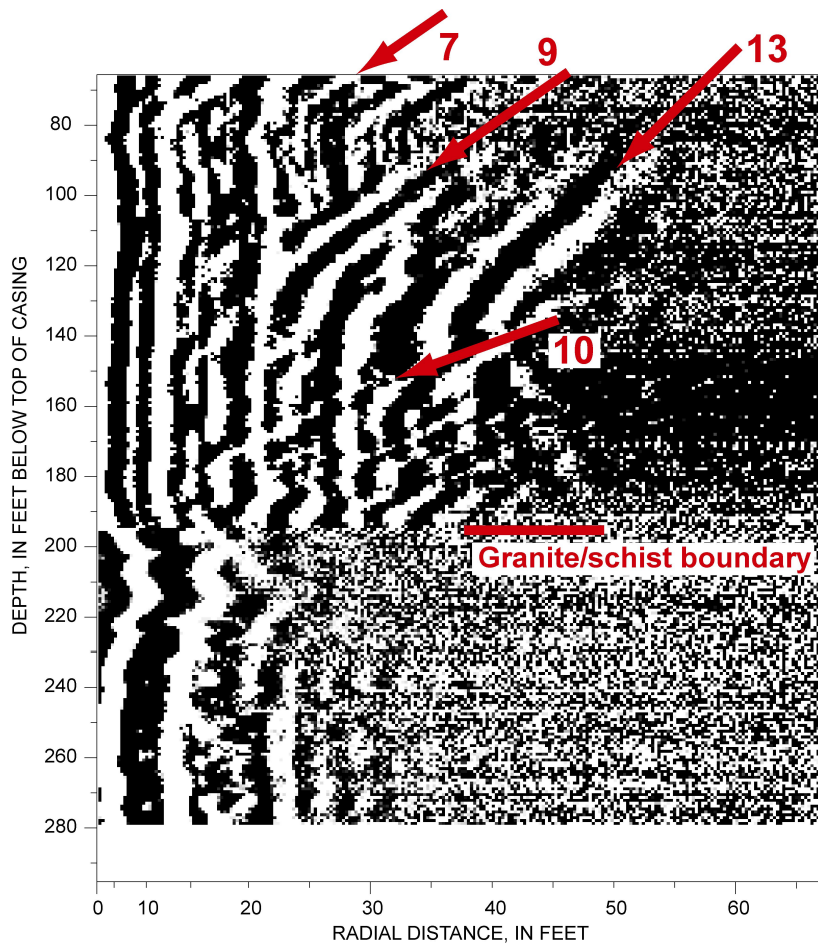


Figure 6. Borehole radar reflection data from well on Property C, in Montville, Connecticut, used to predict location of new well. The red arrows indicate interpreted radar reflectors. The numbers correspond to reflector labels in table 6.

Table 6. Summary of borehole radar reflector data from original well at Property C in Montville, Connecticut

Reflector	Depth below top of casing (feet)	Elevation (feet)	Strike ¹	Dip
1	34.8	148.4	316	33
2	60.7	122.5	226	22
3	101.4	81.8	326	52
4	102.4	80.8	156	72
5	104.0	79.2	196	61
6	128.9	54.3	196	50
7	134.5	48.7	306	68
8	170.3	12.9	206	46
9	186.0	-2.8	106	67
10	190.9	-7.7	216	29
11	207.3	-24.1	246	26
12	221.1	-37.9	116	35
13	238.2	-55.0	116	71
14	267.7	-84.5	326	47
15	288.4	-105.2	206	38

¹Strikes and dips are presented using the right-hand rule where the strike is in degrees east of north, and the dip direction is to the right of the strike.

Table 7. Packer-test results in original well on Property C. Whole-well water-quality results are included for comparison [NS indicates not sampled, because of insufficient yield. NA indicates not applicable. -- indicates no interpreted radar reflectors in this zone.]

Designation ¹	Packer-test zones		Elevation of final head ²	Concentrations (micrograms per liter)		Borehole radar reflector from Table 6
	Depth to center (feet from casing top)	Water purge volume (gallons)		MTBE	Benzene	
a	56.5	NS	161.43	NS	NS	
b	65.5	16.0	162.91	47	6	2
c	74.5	17.0	162.72	49	7	--
d	83.5	7.0	163.23	57	10	--
e	92.5	18.0	162.64	55	11	--
f	123.5	16.0	163.75	72	9	--
g	132.5	33.5	163.33	79	12	6, 7
h	162.5	52.0	163.37	470	330	--
i	171.5	52.5	164.03	970	880	8
j	180.5	57.5	163.55	120	64	--
k	189.5	52.0	163.66	1,100	1,000	9, 10
l	198.5	40.0	162.99	1,200	840	--
Whole well ³	NA	NA	NA	990	660	--

¹ Corresponds to designation of radar reflectors.

² Feet above National Geodetic Vertical Datum of 1929. Not necessarily static head conditions.

³ Whole well indicates a sample collected from the open borehole.

Summary

In consideration of our objective at the three properties, which was to locate and drill into zones of potable water within an otherwise contaminated aquifer, we achieved mixed results. At **Property A**, where the original well contained a single, contaminated water-bearing fracture at the bottom, we were unable to site desirable locations within the bedrock aquifer for potable water exploration. An alternate approach, which was based upon observations of water-bearing fractures in an outcrop, resulted in constructing a new well that also was contaminated. The target drilling depth at **Property B** was selected to avoid the projection of the most contaminated fracture. Uncontaminated since it was drilled in 1995, the new well probably benefited from the combined effects of the desired shallow completion depth and uncontaminated recharge from upslope. **Property C** appears to have benefited the most from the combined logging and discrete-interval testing approach. It is likely that this well tapped an uncontaminated portion of the bedrock aquifer that is recharged by direct infiltration. The proximity of the original well to the new well (30 ft) appears to have been a benefit, rather than a hindrance, because confidence in a particular radar reflector being planar and continuous increases with proximity to the logged well. Therefore, the relatively short distance between wells allowed for greater assurance in selecting a target drilling zone.

Among the geophysical tools used, borehole radar and HPFM provided the most useful information to maximize chances of locating uncontaminated ground water in the bedrock. Caliper and one or both of the other imaging tools (ATV, OTV) also were valuable. At Property B, where only radar was used, we had the benefit of a detailed, accurate well completion report, which identified water-bearing zones and, for practical purposes, was used in place of HPFM data. Radar ultimately proved to be the tool of primary importance at this site.

Conclusions

These case histories suggest that the combined use of borehole geophysics, particularly radar, with discrete-fracture sampling can be used in some cases to identify the locations of less contaminated or uncontaminated fractures at distances of tens of feet from contaminated bedrock wells. Borehole radar is most effective at sites underlain by electrically resistive materials, such as the bedrock in this study area. This approach may be used to improve the chances of successfully siting alternate potable water wells and/or selecting target drilling depths. Likewise, the same data and approach potentially could be used for identifying specific fractures for remediation.

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