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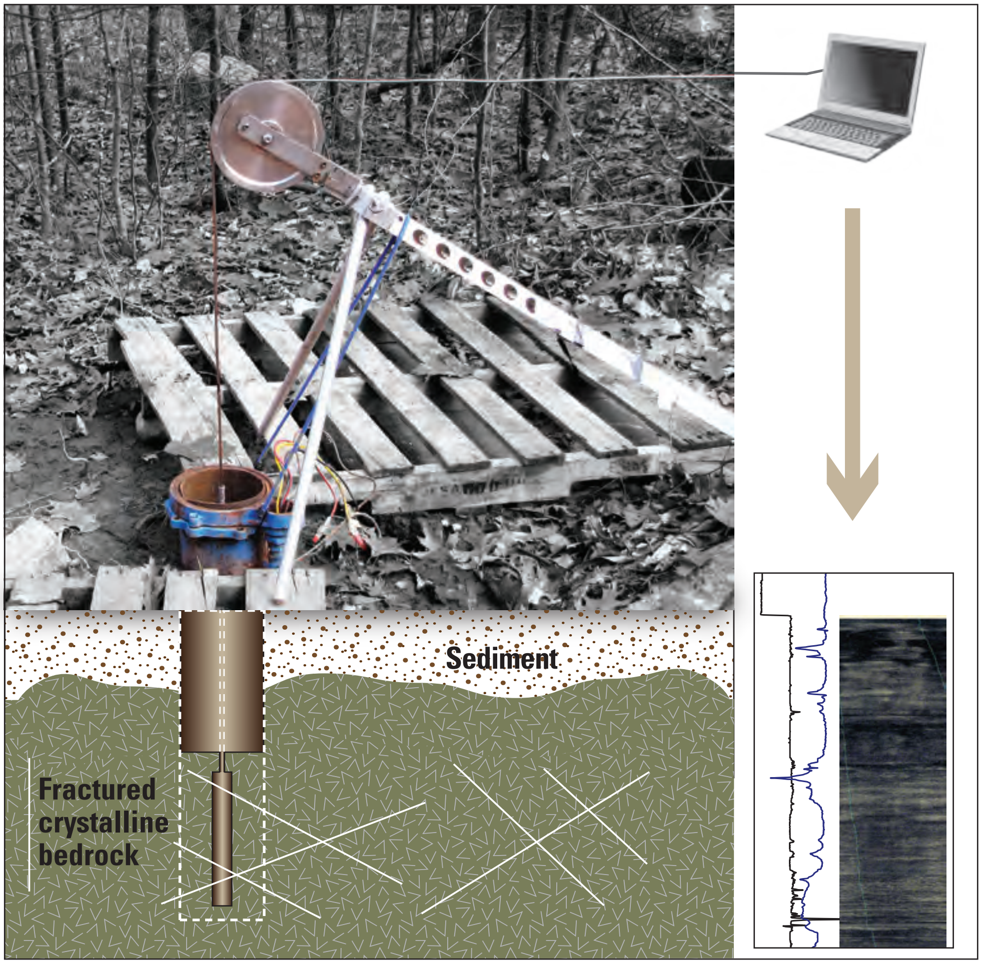
Geophysical and Flow-Weighted Natural-Contaminant Characterization of Three Water-Supply Wells in New Hampshire



Open-File Report 2011–1019

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

Cover. Photograph shows a tripod and cable, used to log a water-supply well, along with a depiction of fractured bedrock, a geophysical probe, and processed data.

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KEN SALAZAR, Secretary

U.S. Geological Survey
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Conversion Factors and Datum

Inch/Pound to SI

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
gallon (gal)	0.003785	cubic meter (m^3)
	Flow rate	
gallon per minute (gal/min)	0.06309	liter per second (L/s)
gallon per day (gal/d)	0.003785	cubic meter per day (m^3/d)

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

$$°F=(1.8×°C)+32$$

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

$$°C=(°F–32)/1.8$$

Vertical coordinate information is referenced to North American Vertical Datum of 1988 (NAVD 88).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

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

Concentrations of chemical constituents in water are given either in milligrams per liter (mg/L) or micrograms per liter (µg/L).

Geophysical and Flow-Weighted Natural-Contaminant Characterization of Three Water-Supply Wells in New Hampshire

By Thomas J. Mack[1], Marcel Belaval[2], James R. Degnan[1], Stephen J. Roy[3], and Joseph D. Ayotte[1]

Abstract

Three bedrock water-supply systems in New Hampshire were studied, using borehole geophysics and flow-weighted sampling techniques, to determine the sources and distribution of natural contaminants in water entering the boreholes and to assess whether borehole modifications might be used to reduce contaminant levels. Well water in more than 100 community water-supply systems in New Hampshire have natural contaminants, such as arsenic and uranium, above the U.S. Environmental Protection Agency maximum contaminant levels of 10 and 30 micrograms per liter, respectively. The water-system wells were studied to identify fractional contributions of natural contaminants from specific fracture zones. The yields and flow-weighted contaminant levels of such fracture zones were assessed to determine if a modification of the borehole might lead to a reduction in the system's contaminant levels.

The water-supply systems investigated were typical of small community water systems in New Hampshire where a water system may serve 100 connections or less. Each water system consisted of two wells, approximately 300 to 400 feet deep, in generally low-yielding (about 10 gallons per minute or less) crystalline bedrock. The wells were typically operated a few hours per day to fill a storage tank and had tens of feet of drawdown caused by the low well yields. The systems selected had contaminant concentrations slightly above MCL, or a low-level contamination. One of the water systems investigated had low-level (10 to 24 micrograms per liter) arsenic contamination, and two of the water systems had low-level uranium (30 to 40 micrograms per liter) contamination. The contaminant values were blended-water concentrations from the two wells in a system. Each water system had differences in contaminant concentrations between the two wells. In each case, the well with the greater concentration of the two was selected for investigation. In two of the three systems investigated, there was either not enough variation in the borehole contaminant concentration or not enough water-yielding fractures for borehole modifications to be a viable potential remedy to elevated contamination. However, borehole and contaminant conditions in one of the bedrock supply-well systems may be favorable to potential improvement of supplied water by borehole modification where selected fracture zones are sealed off from supplying water to the well.

Introduction

Arsenic and uranium are common naturally occurring contaminants in groundwater in bedrock aquifers in New England (Ayotte and others, 1999, 2003, 2007; Moore, 2004; Montgomery and others, 2003; Peters and Blum, 2003; Welch and Stollenwerk, 2003; Robinson and others, 2006). Many bedrock water-supply wells in New England have U.S. Environmental Protection Agency (USEPA) maximum contaminant level (MCL) exceedances of these naturally occurring contaminants. In the case of arsenic, many community water systems in New England have a problem complying with the 10 μg/L (micrograms per liter) arsenic drinking-water standard, and many of such systems have concentrations in the range of 10 to 20 μg/L. In New Hampshire, about 100 community groundwater systems have arsenic in source water in this concentration range. For public water systems with low-level exceedances of naturally occurring contaminants, defined as contaminant concentrations slightly above MCL, a treatment system generally is

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[1] U.S. Geological Survey.

[2] U.S. Environmental Protection Agency.

[3] New Hampshire Department of Environmental Services.

installed to comply with drinking-water regulations. In addition to the costs associated with treatment installation, operation, and maintenance, there also is an added future burden of ongoing disposal of treatment residuals that may contain hazardous levels of arsenic or radionuclides.

In 2008 and 2009, the USEPA, New Hampshire Department of Environmental Services (NHDES), and U.S. Geological Survey (USGS) initiated this study to evaluate borehole characterization methods for identifying natural contaminant flow into bedrock water-supply wells from individual fractures or fracture zones. If natural contaminants in a bedrock water-supply well are found to originate from specific fractures in a borehole, it may be possible to block or modify a section of the borehole to reduce the inflow of the contaminant. This investigation allows for (1) testing of methods at a variety of bedrock supply-well systems, and (2) testing characterization techniques to assess if borehole modifications may provide a cost effective treatment option.

Purpose and Scope

This report presents the results of borehole geophysical well logging and flow-weighted water-quality sampling to determine concentrations of selected natural contaminants in water supplied by three bedrock water systems in New Hampshire. This report presents the methods used to (1) characterize boreholes using standard geophysical tools and sampling techniques; (2) identify the predominant bedrock fractures and the flow-weighted concentration of contaminants contributing to a well; and (3) help identify borehole and contaminant conditions where borehole modifications may help to achieve MCL compliance for naturally occurring arsenic and uranium in bedrock supply wells. This report also describes two alternative approaches for borehole characterization that may warrant application in wells with attributes that differ from the three wells investigated.

Description of Study Area

Many communities in New Hampshire rely on wells completed in fractured crystalline bedrock for their water supply. The quality of groundwater in the bedrock aquifer is generally good; however, occurrences of arsenic and other metals have been found to be associated with lithochemical bedrock groups in areas of the state (Montgomery and others, 2003; Moore, 2004). Bedrock public water-supply well sites with exceedances of naturally occurring regulated contaminants that were slightly greater than (within about 20 percent) the MCL were selected for study. Sites with greater exceedances were not investigated because such sites are less likely to be remediated to levels less than the MCL using borehole modifications. The study area is characterized as a fractured-crystalline bedrock setting where overburden sediments are generally less than 30 ft thick. Water-supply wells in this setting are typically 300 to 500 ft deep with low yields, 10 gal/min or less. The water-supply systems investigated were typically well systems serving small housing developments in rural areas with about 100 service connections. The water systems generally consisted of two water-supply wells installed in fractured-crystalline bedrock, a storage tank, and sometimes chlorination and pH adjustment.

Previous Investigations

In 2006, the NHDES and the USEPA Region 1 evaluated three small drinking-water systems in southern New Hampshire as candidates for borehole modification (Marcel Belaval, U.S. Environmental Protection Agency, written commun., 2007; Stephen Roy, New Hampshire Department of Environmental Services, written commun., 2007). The results of that evaluation indicated that arsenic levels varied by fracture and that borehole modification may be successful at reducing overall arsenic concentrations in well water. On the basis of these preliminary findings, borehole characterization and modifications were believed to provide a potential means for a rapid and inexpensive remediation of low-level naturally occurring contaminants.

Borehole modifications have been used in non-crystalline bedrock settings to remediate naturally occurring arsenic contamination in well water. Smith (2005) found elevated arsenic concentrations in specific sandstone units in Oklahoma that could be selectively removed from the screened zones of public-supply wells to reduce natural arsenic contamination. Halford and others (2010) found selected aquifers composed of lacustrine sediments that could be removed from the screened zones of public-supply wells in California to reduce natural arsenic contamination.

Methods and Approach

The USEPA and USGS worked with the NHDES to identify groundwater-supply systems that had exceedances of selected contaminants slightly (less than about 20 percent) greater than their respective MCLs. Water-supply systems with exceedances greater than 20 percent for the whole well would likely have multiple fractures with elevated concentrations or a few elevated-concentration fractures that constitute a large fraction of the borehole's total yield. Such systems would be less likely to be ameliorated to levels below the MCL by borehole modification and groundwater mixing. Additionally, the study avoided the selection of supply systems that had multiple natural contaminants because modifications of a borehole to reduce one contaminant might result in an increase in another contaminant. The borehole being considered needed to have sufficient yield (greater than 10 gal/min), such that it was likely to have multiple yielding fractures. If fractures are removed from a low-yielding well, by borehole modification, the resultant borehole may not have enough yield to be a reliable water-supply well. Finally, candidate systems needed an owner/operator willing to be part of the study and to be able to remove one well from service during the evaluation for up to 1 week.

In summary, the criteria for investigation included (1) systems that have concentrations of arsenic or uranium that slightly exceeded their respective MCLs (10 and 30 µg/L), (2) systems that have sufficient storage or redundant capacity to allow for a multi-day borehole testing program and owners/operators willing to participate in this study, and (3) the system had individual well yields of at least 10 gal/min. Although tens of supply systems in New Hampshire and Vermont were evaluated for possible investigation, relatively few systems met the necessary study criteria. The three groundwater-supply systems selected for investigation (fig. 1) and the field investigation periods were Francestown, October 2008; Londonderry, June 2009; and Salem, October 2009.

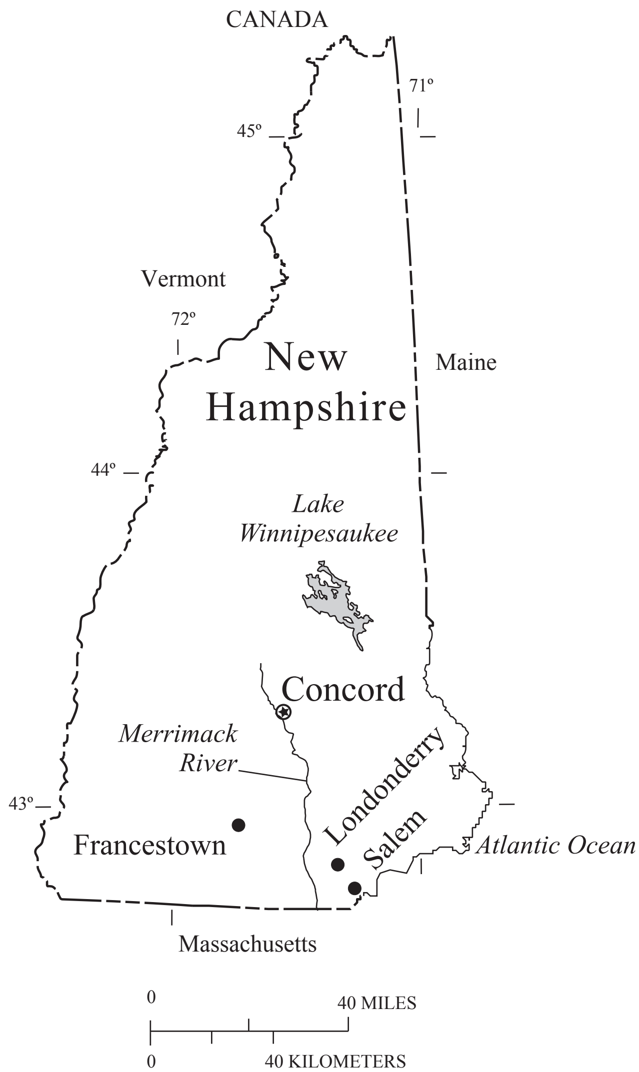


Figure 1. Locations of the water-supply systems investigated in Francestown, Londonderry, and Salem, New Hampshire.

Borehole Geophysics

Standard borehole geophysical logs, including caliper, natural-gamma radiation, electromagnetic induction, and fluid temperature and specific conductance, were collected and are presented for the borehole investigated at each water-supply system. A multiparameter fluid log, which included pH, dissolved oxygen, and oxidation-reduction potential (redox), also was collected at each site. Fluid temperature and conductance logs were collected under ambient (non-pumping) and low-flow (approximately 1 gal/min) pumping conditions. All results are referenced in feet below top of casing (TOC). A description of standard borehole geophysical logging methods and interpretation is given by Keys (1990).

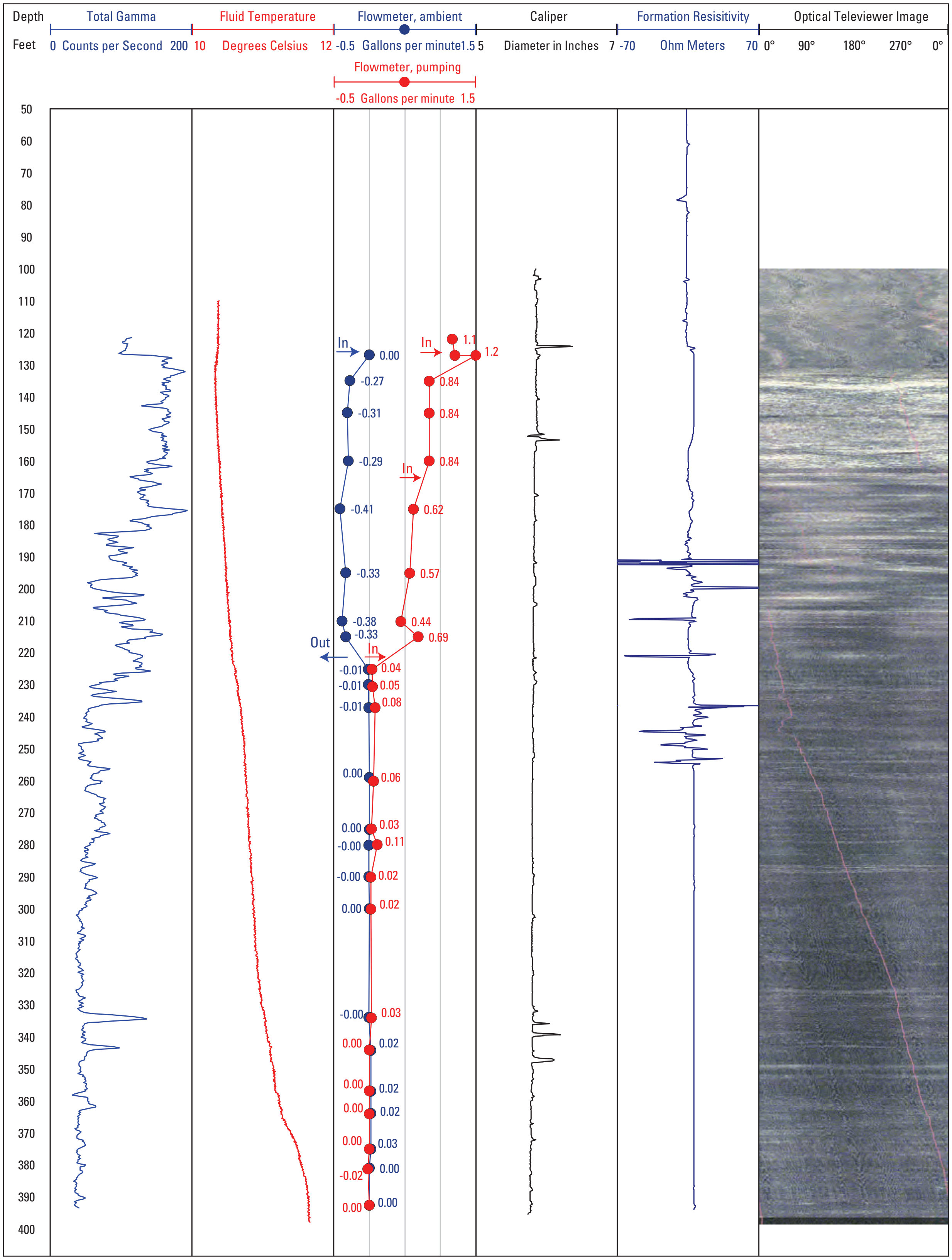
Optical televiewer logs were collected to further identify fractures and to confirm areas of competent borehole wall for heat-pulse flowmeter measurements. Where a hydraulic connection with another borehole in the water system was apparent, or suspected, the orientations of selected features were described. Standard and televiewer logs were used to identify zones for flowmeter logging. A description of optical televiewer logging methods is given by Johnson (1996).

Heat-pulse flowmeter measurements were made under ambient flow and under low-flow pumped conditions. Where it was difficult to obtain stable (steady state) conditions in the borehole, due to interferences of a second well or unknown influences, heat-pulse flowmeter data were difficult to interpret quantitatively. If the water levels in the borehole investigated were affected by unavoidable withdrawals in the systems second supply well, additional heat-pulse flowmeter measurements were made to qualitatively investigate fracture connections. Negative values (for example, see fig. 2) indicate downflow, and positive values indicate upflow. Flow directions, upflow or downflow in the borehole, and relative amounts were compared to determine flow in and out of the borehole (Keys, 1990). Flow measurements were repeated at individual measurement points in the borehole to assess the variability of flow in the borehole and potential magnitude of measurement error or the occurrence of transient flow disturbances. Repeated measurements indicated that measurement error in some cases was potentially as low as 0.001 gal/min (gallons per minute). However, repeated measurements also indicated variations between measurements at a point that were caused by undetermined factors such as changes in flowmeter pumping rates; pumping at the second well in the water system; or other transient flow disturbances from an unknown source, such as another withdrawal well close enough to affect the measured borehole. The standard deviations of variations in flow were usually between 5 and 10 percent of the flow measurement. Measurements that were greater than 10 percent of other flows at a point and were not repeatable were ignored; the remaining measurements were used to provide an average flow measurement.

Groundwater Sampling and Water-Quality Analysis

Untreated whole-well water reconnaissance samples were analyzed for arsenic and uranium by the USEPA New England Region; discrete interval samples were analyzed by the NHDES Water Laboratory. Reconnaissance water samples were collected with the production pump from the open borehole (whole well) and represent a flow-weighted average of all the water-producing fractures in the borehole on the basis of their transmissivity (Shapiro, 2002). After reconnaissance samples were evaluated, the existing submersible pump was removed so that geophysical logs could be collected in the open borehole (see discussion on geophysical logs in the previous section) and analyzed to select discrete intervals for flowmeter and sampling analysis.

While the pump for the supply well was shut off and removed from service, some groundwater flow in the borehole may have moved water from one part of the aquifer system to another. Prior to water-quality sampling, an assessment of the potential volume of water distributed in the borehole through ambient (non-pumping) flow while the supply pumps were off, termed intraborehole flow, was made to quantify that volume of water before sampling. An amount of water at least equal to the intraborehole flow was removed from each borehole. Because of stagnant intervals in the borehole and differential removal of water during low-flow pumping, that amount of water may not necessarily represent all the water that flowed from one zone of the borehole to another during ambient conditions. For example, the water at the base of a borehole with few or no transmissive fractures may have very little intraborehole inflow water, but any stagnant water in that zone of the borehole will also not be removed during low-flow pumping from the top of a well.



EXPLANATION

All measurements are in feet below the top of the casing.

Blue—Ambient flow in the logged well
Red—Pumping in the logged well

Circle shows measurement point; flowmeter line shows general trend.
Negative numbers indicate downflow; positive numbers upflow.
Arrows show points of inflow or outflow to the borehole.

Figure 2. Borehole geophysical logs for well FBRW-1, Francestown, New Hampshire, 2008.

During the study, borehole groundwater was sampled at depths above and below selected transmissive fractures, identified by changes in borehole fluid properties or flow using borehole geophysical logs. Depth-integrated samples were collected using a fluid sample chamber that was activated by compressed nitrogen to capture and seal the water sample at a specific depth for retrieval. Each sample represented a composite of the arsenic or uranium concentrations from all contributing fractures or zones below the sampling device. Samples were collected from top to bottom of the borehole to minimize disturbance of the borehole walls and to reduce the effects of turbidity in the borehole. The contaminant concentrations in each flow zone were subsequently calculated from borehole-flowmeter data and the laboratory results.

The NHDES Water Quality Laboratory analyzed water samples for uranium and arsenic using inductively coupled plasma mass spectrometry, according to USEPA method 200.8. The laboratory reporting level (LRL) for the study was 1 µg/L using USEPA method 200.8. The USEPA New England Regional Laboratory analyzed arsenic samples from the Francestown system by the graphite furnace method with a LRL of 10 µg/L. This higher LRL was acceptable for the range of concentrations at this system. Replicate, equipment blank (from arsenic- and uranium-free water), and discharge time-variant samples were collected throughout the investigation (approximately every 10, 3, and 3 samples, respectively). One of the three sequential replication samples had a 5.3 relative percent difference; this test is meant to analyze sample collection reproducibility. None of the 11 equipment blank samples had a measurable concentration of arsenic or uranium. Split replicate performance-evaluation samples (designed to test lab result reproducibility) prepared using environmental samples had a 0 percent relative percent difference. Time-variant samples, collected throughout each test and borehole site, showed the contaminant level varied up to 14.3 percent (a range in whole well arsenic concentrations of 21 to 24 µg/L at Francestown) over the period of sampling (appendix 1). Time-variant sample results were considered on a site-by-site basis because they are influenced by transient-flow conditions in the borehole and in the bedrock aquifer, which may be caused by fluctuations of the pump rate, previous ambient intraborehole flows, or unknown conditions such as other nearby withdrawals. The quality-assurance data indicated the environmental data were acceptable, and there was little potential bias due to sampling. However, time-variant relative percent difference values of up to 14.3 percent indicated that pumping during sampling either did not overcome ambient intraborehole flow displacement or nearby pumping influences, or that the water quality in the aquifer is not uniform, or a combination of these factors.

Flow-weighted contaminant contributions were calculated using an equation described by Izbicki and others (1999):

$$C_a = (C_i Q_i - C_{i+1}\, Q_{i+1})/Q_a \,, \qquad (1)$$

where

- C is the contaminant concentration,
- Q is the flow of water within the well,
- i is the first sample collection and flow measurement depth,
- $i+1$ is the second or subsequent sample collection and flow measurement depth, and
- a is the interval between i and $i+1$.

Equation 1 provides a means to differentiate variations in sample concentrations that can be attributed to zones of inflow with depth. By this method, inflows must be quantified and the water quality must be sampled at multiple points along the borehole. The more points along the borehole that are logged for flow and sampled, the finer the flow-weighted contaminant zones in the borehole can be delineated. However, because a flow term is in the denominator of equation 1, small variations in flow result in unrealistically high flow-weighted concentrations. Where flow in the well stayed the same between sample depths or decreased, which occasionally occurs with low-flow sampling because of external factors, flow-weighted concentrations could not be calculated. Therefore, flow variations of less than 5 percent were considered to be negligible and were not evaluated in flow-weighted concentrations.

Borehole Flow and Water Quality Characterization

Three bedrock groundwater-supply systems were selected for investigation between October 2008 and November 2009 on the basis of the criteria described previously. Each supply system had unique water-use, borehole, and water-quality characteristics.

Francestown

The water system investigated in Francestown consists of 2 wells, located about 300 ft apart, that serve a community of 145 people. Francestown bedrock well FBRW-1 was installed prior to 1984 and, therefore, is not listed in the NHDES database of well-completion reports. This well was reported as being drilled to 370 ft, with a 0.5-ft diameter steel casing installed and a yield of 3 gal/min. During the investigation, well FBRW-1 was determined to be 392 ft deep, from TOC, with 126 ft of casing. Well FBRW-1 was hydrofractured in 2005 and was reported to obtain a yield of 10 gal/min.

Francestown well FBRW-2 was installed to 400 ft, using 0.5-ft diameter 126 ft-long steel casing, with a yield of approximately 3 gal/min. Well FBRW-2 was hydrofractured in 2002 and was reported to obtain a yield of 8 gal/min. Between August 2006 and April 2008, the arsenic concentration for blended water samples (water from both wells blended together) ranged from 10.0 to 11.1 µg/L. In 2008, the water system delivered water at a rate of approximately 6,000 gal/d (gallons per day), and well FBRW-1 accounted for about 60 percent of the total water supply. Water samples collected from the individual wells on October 8, 2008, by this project and analyzed by NHDES had arsenic concentrations of 14.6 µg/L for well FBRW-1 and 2.7 µg/L for well FBRW-2. On the basis of these results, well FBRW-1 was selected for investigation. The well pump at FBRW-1 was turned off on Saturday, October 17, and removed from the borehole Monday morning, October 19, 2008.

The area of the well field is on a mapped northeast-southwest trending approximate contact between metasedimentary rocks—the Perry Mountain Formation to the northwest and the Smalls Falls Formation to the southeast, both of Silurian age; a similar trending contact with the Kinsman Granodiorite, of Devonian age, is mapped about 500 ft southeast of the wells (Lyons and others, 1997). Greene (1970) shows the Kinsman Granodiorite near the location of the wells with a northwest dipping contact that trends toward the supply wells. The Perry Mountain Formation consists of sharply interbedded quartzite, metapelite, and metaturbidites with common coticule (fine-grained quartz garnet) layers. The Small Falls Formation is a rusty weathering thin-bedded sulfidic-graphitic schist and pyrrhotitic calc-silicate granofels. The Kinsman Granodiorite is commonly identified by large crystals of potassium feldspar in a finer matrix of foliated granite, granodiorite, tonalite, and minor quartz diorite. At well FBRW-1, the surficial sediments consist of approximately 115 to 125 ft of glacial till (based on indications from the gamma log). Well FBRW-2 also penetrates through the till; however, kame terrace deposits are within a few hundred feet west of the well (Hildreth, 1990).

Borehole Geophysical Logs

Geophysical logs collected at well FBRW-1 indicated the depths and characteristics of fractures in the borehole (fig. 2). The optical televiewer log was expanded (not shown) to examine the borehole wall in detail to help locate fracture zones and provide measurement points for the heat-pulse flowmeter. All depths given are from TOC. The two water-supply wells were determined to be hydrologically independent on the basis of the water-level responses. The water level in well FBRW-1 recovered prior to collection of the borehole logging data, and well FBRW-2 remained in use for water supply. Therefore, ambient (non-pumped) and low-flow pumped borehole flow measurements were made under stable conditions.

During ambient conditions, water enters the well at 0.3 gal/min at about 128 ft, flows down the borehole with minor inflows and outflows (of about 0.1 gal/min), and flows out of the well at 222 ft. Borehole flows, ambient and low-flow pumping, below 222 ft (fig. 2) were not significant (much less than 0.1 gal/min). Flow was measured at the fracture at 128 ft but flowmeter measurements above and below the bottom of the casing (126 ft) did not indicate flow (leaking) at the bottom of the casing.

Stressed flowmeter measurements were made while pumping at approximately 1 gal/min at the water surface (70 ft) under steady-state (stable water-level) conditions. On the basis of variations between measured flows, flows less than 5 percent of the total inflow were not considered meaningful. Inflows below 334 ft were minor, and inflows below 280 ft were about 5 percent of the total flow. Approximately 50 percent of the total inflow was at 222 ft, 21 percent at 128 ft, and minor inflows (less than 10 percent) were measured at about 172 and 205 ft.

Water Quality and Flow-Weighted Chemical Constituents

Ambient flow in the borehole during the period that well FBRW-1 was not pumping (between Saturday morning and Monday morning) was estimated to result in approximately 1,150 gal of water flowing down the borehole from the upper bedrock unit to the lower bedrock unit. Prior to depth-discrete sampling on October 23, 2008, approximately 1,560 gal of water was pumped out of the well. On the basis of these calculations and the estimates of fracture contributions determined above, it is likely that water from the primary fracture (222 ft), not recent inflow from upper zones, was sampled. If casing storage and stagnant areas at the base of the borehole are factored in, more water may have been withdrawn from the primary fracture prior to sampling. Time-variant sampling indicated that contaminant concentrations varied by as much as 15 percent during sampling (appendix 1). It is unclear whether these variations were due to intraborehole flow that occurred while the borehole was not pumped or if such variations naturally occur in the bedrock aquifer.

Analysis of the borehole logs (fig. 2) indicated that, under low-flow pumping conditions, water enters well FBRW-1 primarily from fractures located at 128 and 222 ft; relatively less water enters at 172 and 205 ft. Water samples were collected above and below each fracture while pumping the well and at other selected points in the borehole (table 1). The flow-weighted arsenic concentration from each fracture was calculated on the basis of an integration of flowmeter and water-quality analyses. Analysis of whole-well water samples collected on October 23, 2008, indicated a 3 µg/L time-variation in arsenic concentration at the borehole.

Table 1. Depth of fractures, sampling depth, flow fraction, arsenic concentration, and flow-weighted arsenic concentration for water sampled from well FBRW-1, Francestown, New Hampshire, 2008.

[Samples were analyzed at the New Hampshire Department of Environmental Services Water Quality Laboratory; ft, feet below top of casing; µg/L, micrograms per liter; --, not calculated]

Dominant fractures (ft)	Zone investigated (ft)	Water sample depth (ft)	Borehole zone flow (cumulative fraction)	Sample arsenic concentration (µg/L)	Flow-weighted borehole zone arsenic concentration (µg/L)	Comment and primary flow zones
		100	1	21		In casing, whole well
126, 128	100–135				23	At base of casing
		135	0.7	20		
142, 152	135–160				--	
		160	0.7	19		
172	160–180				19	Flow
		180	0.62	19		
192	180–196				--	
		196	0.62	18		
205	196–210				10	
		210	0.55	19		
213, 222, 227, 232	210–240				19	Flow
		240	0.05	23		
	240–320					
		320	0	22	--	
254	320–380					
		380	0	13	--	

The fractures at 172 and 222 ft had calculated arsenic concentrations of about 19 µg/L, and the fracture at 128 ft had a calculated arsenic concentration of 25 µg/L. The results are summarized in table 1 showing depth, percentage of water inflow in the borehole, sample arsenic concentration, field parameters, and calculated flow-weighted arsenic concentrations.

Whole-well arsenic concentrations in groundwater at well FBRW-1 were between 21 and 24 µg/L (appendix 1). The fracture zone between 196 and 210 ft had the lowest flow-weighted arsenic concentration (10 µg/L, table 1). However, this zone contributed only a little more than 10 percent of the total flow in the borehole and would not sustain the flow rates needed for supply purposes. Because of the small difference in arsenic concentration detected (19 to 23 µg/L) between the other water-bearing fracture zones, it was determined that borehole modification would not reduce arsenic concentrations enough to reduce the arsenic level below the MCL of 10 µg/L. Although the fracture at 128 ft is producing slightly higher levels of arsenic, it is only contributing a small portion of the total flow into the borehole (about 21 percent); therefore, the total contribution of arsenic to the well water by removing the water from this fracture is very small, approximately 1 µg/L.

Londonderry

The water system investigated in Londonderry consisted of 2 bedrock wells, located about 50 ft apart, that serve approximately 130 people. The wells LBRW-1 (USGS NH-LRW-937) and LBRW-2 (USGS NH-LRW-938) were reported to be 355 and 400 ft deep with yields of about 10 gal/min. Each borehole has a 6-in. steel casing set into bedrock (about 20 ft below land surface) and a PVC well seal extending to 68 ft below land surface (determined by induction and caliper logs). The well seals were installed in 1990 to address a reported bacterial contamination problem.

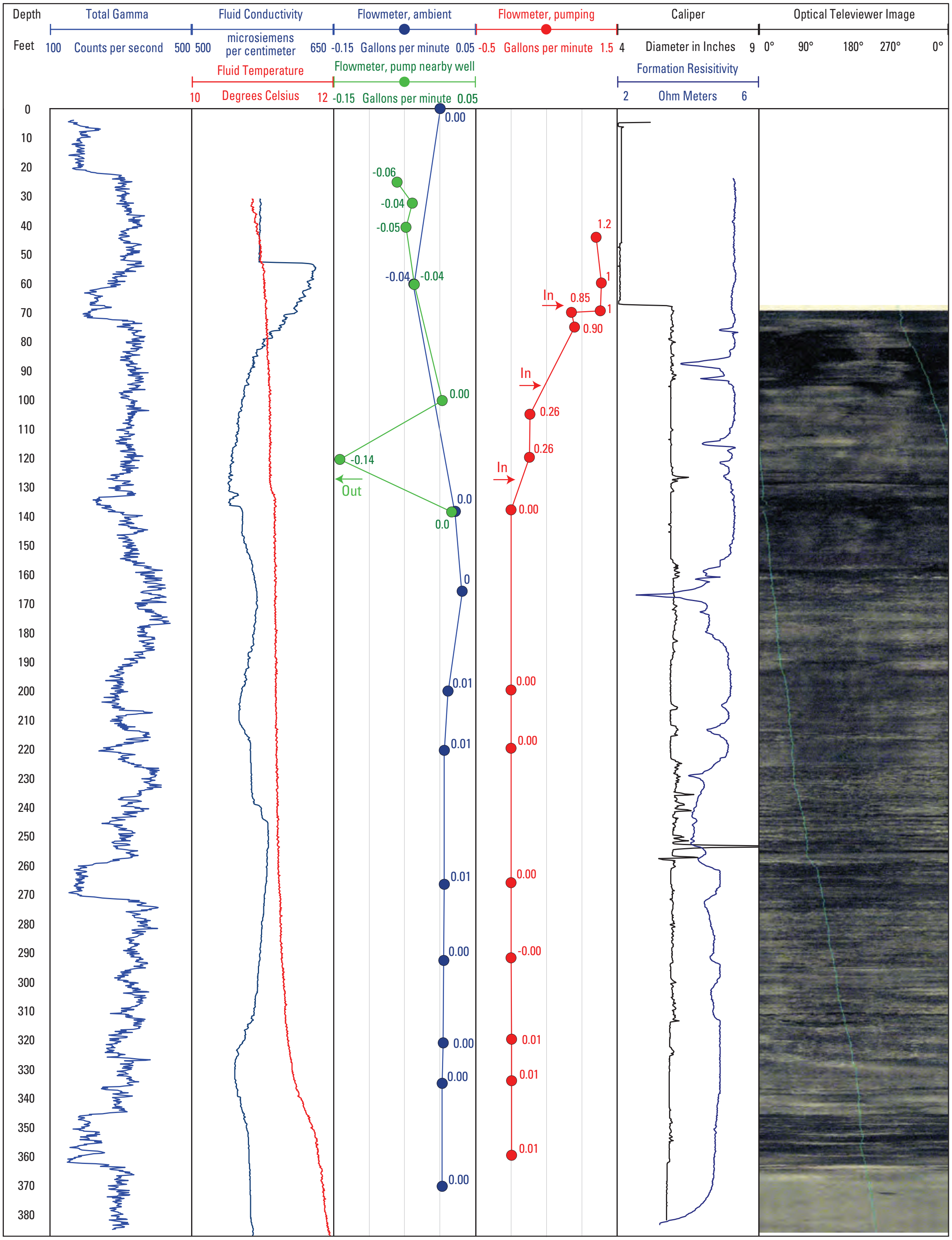
Wells LBRW-1 and LBRW-2 are located within the approximate boundary of a muscovite granite pluton of the New Hampshire Plutonic Suite of Devonian age (Walsh and Clark, 1999). This portion of the pluton is elongated in the northeast-southwest direction and is in contact with the Berwick Formation of Silurian-Ordovician age on each side. Walsh and Clark (1999) map the Berwick Formation in this area as a biotite-plagioclase-quartz granofels and schist and calc-silicate rock. Surficial geology at the site determined from the natural-gamma log consists of 20 ft of glacial till. About 500 ft southeast of the wells is a contact with lake-bottom deposits consisting of sand and silt (Larsen, 1984), in a northeasterly trending swale containing a brook. The wells are in a low-lying area, and the water table was noted to be at the land surface at the time of the study.

When investigated, the water system had been withdrawing water from both wells with a blended uranium concentration of 30 to 40 µg/L in 2008. Samples collected during a site visit on May 5, 2009, had uranium concentrations in the wells of 26 (LBRW-1) and 54 µg/L (LBRW-2). On the basis of these results, well LBRW-2 was selected for characterization.

Borehole Geophysical Log Analysis

Analysis of the geophysical logs showed that well LBRW-2 had few large fracture zones (caliper log, fig. 3). Prominent fractures were measured at 129, 255, and 382 ft (bottom of the borehole). The fracture at 255 ft spans nearly 1 ft of borehole length and is essentially horizontal. The fracture at 129 ft is also nearly horizontal. The gamma log indicated some distinct zones of rock that appear darker and nearly horizontal in the optical log, at 260 to 270 ft and 345 to 362 ft. Trends in the temperature log (fig. 3) did not indicate any prominent flow zones but did indicate likely stagnant water below about 320 ft. Oxygen and redox in the fluid multiparameter log (not shown) indicated fluid contrasts at 265 ft (non-pumped) and at 290 ft (pumped) that are likely due to stagnant water in the base of the borehole. Fluid conductance (fig. 3) and oxygen, from the multiparameter log, indicated a fluid chemistry contrast at about 50 ft that together with caliper deflections (45 ft) indicated a possible leak in the PVC casing and groundwater inflow between 45 and 50 ft.

Heat-pulse flowmeter measurements (fig. 3) made while pumping approximately 1.2 gal/min from the top of the water column indicated little flow (near zero) below 140 ft, total inflow to the borehole of 22 percent at 128 ft, 53 percent at 95 ft, and 25 percent at about 69 ft or just below the casing. The ambient flowmeter log (not shown) indicated that without pumping and with stable heads in the well field, there was essentially no flow in well



EXPLANATION

All measurements are in feet below the top of the casing.

Blue—Ambient flow in the logged well Circle shows measurement point; flowmeter line shows general trend.
Red—Pumping in the logged well Negative numbers indicate downflow; positive numbers upflow.
Green—Pumping in adjacent well Arrows show points of inflow or outflow to the borehole.

Figure 3. Borehole geophysical logs for well LBRW-2, Londonderry, New Hampshire, 2009.

LBRW-2. Flowmeter measurements made while well LBRW-1 was operating indicated that water flows down the LBRW-2 borehole, from just below the casing, and leaves well LBRW-2 at 129 ft. During this test, water is also flowing up the borehole from zones above about 280 ft and leaves the borehole at 129 ft. With well LBRW-1 pumping, about 83 percent of the water leaving well LBRW-2, at 129 ft, comes from above this point and 17 percent from below this point. The possible casing leak between 45 and 50 ft could not be definitively confirmed with flowmeter measurements.

During collection of borehole logs, it was observed that wells LBRW-1 and LBRW-2 were highly interconnected, pumping in LBRW-1 would cause rapid drawdowns in LBRW-2, and both wells recovered rapidly from drawdowns. For example, after withdrawals at well LBRW-1 ceased, drawdowns at LBRW-1 and LBRW-2 recovered from 35 and 18 ft, respectively, to about 4 ft in less than an hour. The geophysical logs, water-level response, and the proximity of the wells to each other indicated a likely direct and nearly horizontal connection at 129 ft.

Water Quality and Flow-Weighted Chemical Constituents

On the basis of the borehole logs, groundwater samples were collected on June 17, 2009, at 60, 100, 145, 200, 300, and 380 ft to bracket fractures, fracture zones, or fluid-property changes measured in the borehole. Depth-integrated samples were collected while water was withdrawn from the top of the water column in the borehole under stable head conditions.

Flow-weighted uranium concentrations in well LBRW-2 were calculated for two conditions—with the well pumped at the water table and with well LBRW-1 not pumping, and with well LBRW-1 pumping, assuming all water leaves well LBRW-2 at the fracture at 129 ft (table 2). Flow-weighted concentrations of 52, 59, and 54 µg/L represent water from below 145 ft, from the fracture at 129 ft, and from between 100 ft and the bottom of casing (69 ft), respectively. The small variation of uranium concentrations in the borehole (range of 7 µg/L) indicated that borehole modifications would not be useful in altering the uranium concentration of the water pumped from well LBRW-2 to levels less than the drinking-water standard. However, on the basis of water-level observations in wells LBRW-1 and LBRW-2, it was determined that LBRW-1 has a sufficient yield to serve as the sole community water supply, allowing LBRW-2 and its higher uranium concentration to serve only as an emergency backup.

Using the borehole uranium concentrations determined above, and assuming a direct hydraulic connection at 129 ft to well LBRW-1 and similar uranium concentrations as measured during low-flow sampling, it was estimated that well LBRW-2 contributes an inflow of 50 µg/L to well LBRW-1 from the fracture at 129 ft. If the zone of elevated uranium concentration above 60 ft (54 µg/L) were sealed, the estimated concentration leaving the borehole at 129 ft would be slightly reduced to 45 µg/L. Given that the whole-water uranium concentrations measured at wells LBRW-1 and LBRW-2 were markedly different (26 and 54 µg/L, respectively), it is possible that the fractures contributing water to LBRW-1 have very different uranium concentrations than those contributing to LBRW-2. The fracture zone at 129 ft (fig. 3) in well LBRW-2 is a relatively horizontal fracture (determined by optical televiewer log), and because well LBRW-1 is very close to well LBRW-2 (50 ft), this fracture likely dominates the hydraulic characteristics of LBRW-1 in the same manner as LBRW-2. Water-level monitoring during the investigation indicated that the two wells were highly connected hydraulically (each well responded rapidly to pumping in the other well). If the fracture at 129 ft contributes 40 percent of the flow into well LBRW-1 with a uranium concentration of 50 to 59 µg/L, flow from this fracture might contribute a large fraction of the total uranium concentration measured in LBRW-1. Without inflow from this fracture, the uranium concentration in well LBRW-1 may possibly be less than 20 µg/L. If this zone has hydraulic characteristics similar to the hydraulic characteristics of this same zone in well LBRW-2, it would account for about 22 percent of the well yield.

Table 2. Depth of fractures, sampling depth, flow fraction, uranium concentration, and flow-weighted uranium concentration for water sampled from well LBRW-2 for two pumping scenarios, Londonderry, New Hampshire.

[Samples were analyzed at the New Hampshire Department of Environmental Services Water Quality Laboratory; ft, feet below top of casing; µg/L, micrograms per liter; gal/min, gallon per minute; --, not calculated]

Dominant fractures (ft)	Zone investigated (ft)	Water sample depth (ft)	Borehole zone flow (cumulative fraction)	Sample uranium concentration (µg/L)	Flow-weighted borehole zone uranium concentration (µg/L)	Comment and primary flow zones
Scenario A. Sampling of LBRW-2 while pumping 1.2 gal/min at the water surface in LBRW-2.						
		45		54		In casing, whole well
45–50	45–60		1		--	Possible casing leak
		60		54		Above casing bottom
69, 95	60–100		1		50	Flow
		100		59		
129	100–145		0.42		59	Flow
		145		52		
158, 213, 255, 314	145–bottom		0.01		52	

Dominant fractures (ft)	Zone investigated (ft)	Water sample depth (ft)	Borehole zone flow (relative fraction)	Flow-weighted borehole zone uranium concentration (µg/L)	Estimated fracture uranium concentration (µg/L)	Comment and primary flow zones
Scenario B. Estimated flow-weighted concentrations of uranium in water leaving LBRW-2, at 129 ft, while LBRW-1 operating (assuming all flow leaves borehole LBRW-2 at 129 ft).						
45–50	45–60		0			
		60				
69, 95	60–100		0.83	50		Inflow
		100				
129	100–145		--		50	Outflow
		145				
158, 213, 255, 314	145–bottom		0.17	52		Inflow

Salem

The water system investigated in Salem consisted of 2 bedrock wells, about 45 ft apart, that serve approximately 213 people (fig. 1). Well SBRW-1 is operated as a primary or lead well, and well SBRW-2 supplies additional water to the system as needed. The reported yields of the wells were 55 and 15 gal/min for wells SBRW-1 and SBRW-2, respectively, and combined water uranium concentrations of approximately 10 to 88 µg/L, with a median of 40 µg/L. Samples collected during a site visit (September 19, 2009) had uranium concentrations of 30 µg/L for well SBRW-1 and 32 µg/L for well SBRW-2. Well SBRW-2 was selected for characterization for analysis because it had a slightly higher uranium concentration.

Wells SBRW-1 and SBRW-2 are located on a northeast-southwest trending approximate contact between two units of the Berwick Formation of Silurian-Ordovician age. A southwest strike, northwest dipping approximate contact with a binary granite of the New Hampshire Plutonic Suite of Devonian age is located about 500 ft to the southeast, and a syncline axis with a similar strike is adjacent to the wells to the northwest (Walsh and Clark, 1999). The Berwick Formation is a biotite-plagioclase-quartz granofels and calc-silicate rock; one unit contains schist, and the other quartzite. Surficial deposits at the well field consist of glacial till, and swamp deposits were about 1,000 ft west of the well field (Larson, 1984).

Borehole Geophysical Log Analysis

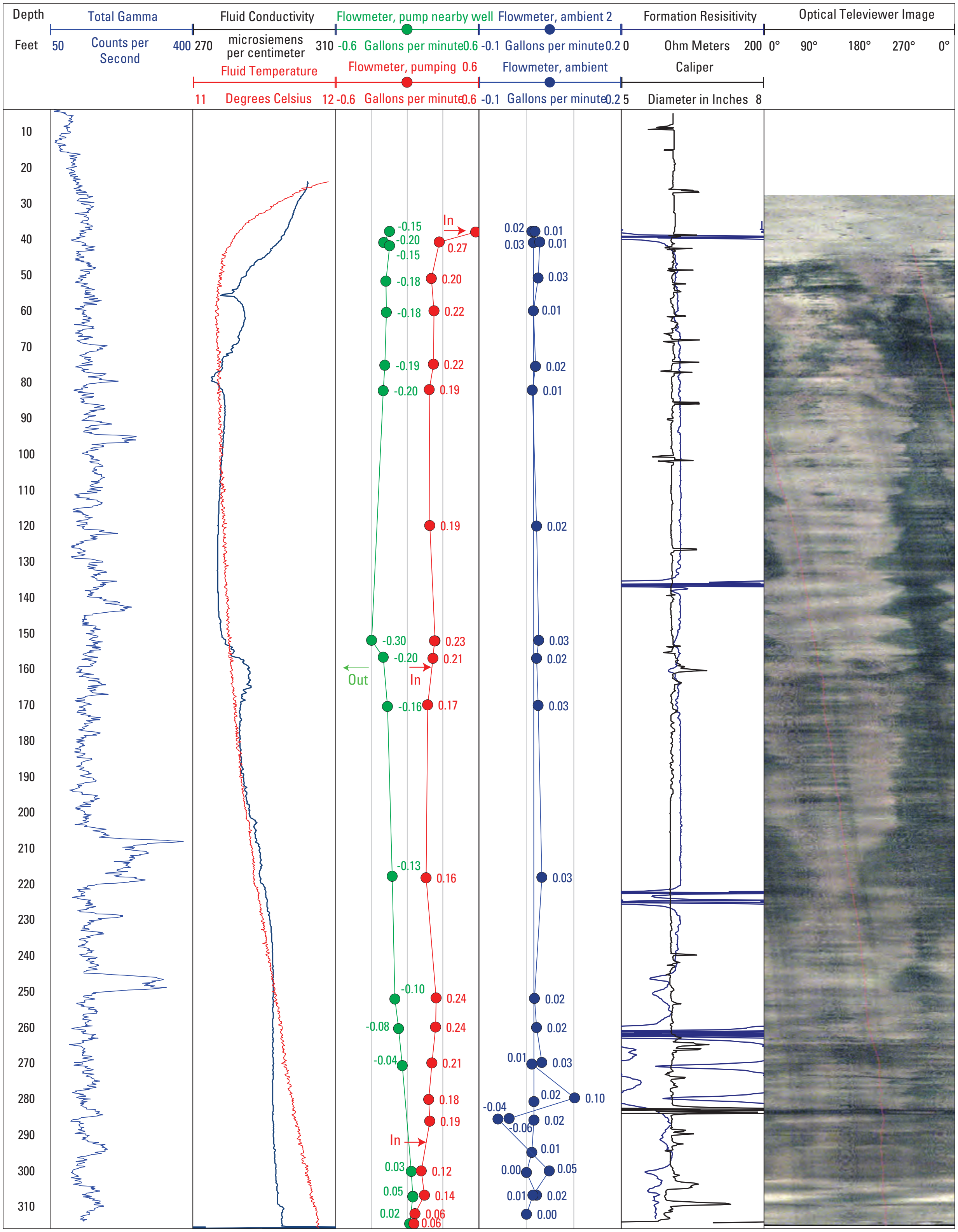
Analysis of the borehole logs of well SBRW-2 indicated relatively few geologic contrasts in the borehole (fig. 4). The rock at the bottom and top of the hole is felsic and fine- to medium-grained binary granite, the darker rock observed in the rest of the hole is likely the schist unit of the Berwick Formation. The gamma log indicated somewhat uniform lithology with the exception of zones at 207 to 220 ft and 245 to 250 ft. The caliper log indicated numerous small fractures, with less than a 7-in. caliper span, from the bottom of the casing (38 ft) to about 85 ft. Minor fractures were noted at 150 and 160 ft that coincide with changes in fluid conductance. Other minor fractures (less than 7 in.) were measured at 265, 304, and 309 ft. A large fairly horizontal fracture, spanning at least 11 in. in diameter (out from the center of the borehole) was measured from 283 to 284 ft. The fluid-conductance log indicated a slight fluid contrast at about 150 to 160 ft and a constant fluid thermal gradient increase below that depth indicative of relatively little water movement.

The pump in well SBRW-2 was removed 3 days before borehole logging; however, withdrawals at well SBRW-1 caused a delayed response in SBRW-2. The delayed response led to constantly changing (unstable) heads in SBRW-2 that made quantitative flowmeter analysis difficult (fig. 4). For example, small (less than 0.03 gal/min) upward flows measured while well SBRW-2 was not pumped were attributed to recovering (rising) water levels and not ambient borehole flows. Although transient (non-repeatable) flows were noted at 283 ft, the non-pumped (ambient) flowmeter log (fig. 4) indicated relatively no flow changes with depth. On the basis of flowmeter measurements with a withdrawal of 0.6 gal/min at the water surface in well SBRW-2, inflows greater than 5 percent of the withdrawal rate were measured and attributed to fractures at the bottom of the well (6 percent), 309 ft (13 percent), 280 ft (12 percent), 160 ft (8 percent), 78 ft (6 percent), 49 ft (11 percent), and at the bottom of the casing (50 percent). The inflow percentages do not add up to 100 percent because there were flow changes that were attributed to lesser inflows and outflows (less than plus or minus 5 percent) along the borehole. However, moderate outflows were attributed to fractures at 226 to 240 ft (-14 percent) and at 126 ft (-8 percent). Considerable inflow (50 percent) was measured at the base of the casing and may represent inflow of water stored in the overlying till sediments. It is also notable that essentially no flow was detected at the large fracture at 283 ft at the pumping rate used in these tests. A qualitative borehole flowmeter test was conducted with no pumping in well SBRW-2 at the initiation of pumping in well SBRW-1. Although flow conditions in the well were transient, it appeared that flow leaves well SBRW-2 at a number of points along the borehole; however, the fracture at 160 ft may have a greater hydraulic connection to well SBRW-1 than other fractures in SBRW-2.

Water Quality and Flow-Weighted Chemical Constituents

Groundwater samples were collected on November 4, 2009, at depths selected on the basis of geophysical logs while water was withdrawn from the top of the water column at a rate of approximately 0.6 gal/min with stable head conditions. Field constituents and laboratory uranium results are listed in appendix 1.

Flow-weighted uranium concentrations presented in table 3 are based on the sampling results and borehole log analysis. At sections of the borehole, such as sections from 252 to 220 ft and 150 to 120 ft (fig. 4), decreases in flow were measured from one interval to shallower intervals, which present complications for calculating flow-weighted concentrations. The change in flow may be caused by transient flow conditions during borehole logging due to unsteady pumping in well SBRW-2, interference from pumping at SBRW-1, or other unknown causes. However, the magnitudes of such flow changes likely represent negligible flow-weighted inflows or outflows of uranium. The flow-weighted concentrations from the fracture zone at about 274 ft yielded a fracture concentration of 59 µg/L (table 3); however, this inflow may not be meaningful on the basis of the variations in sample concentrations that were close to the whole-water sampling variations. The inflows throughout the borehole above 270 ft were likely not substantially different from each other and indicated that uranium inflow concentrations were low. If the fractures below 270 ft were removed from the borehole flow system, the uranium concentration of the whole well was estimated to be 28 µg/L, or essentially unchanged.



EXPLANATION

All measurements are in feet below the top of the casing.

Blue—Ambient flow in the logged well
Red—Pumping in the logged well
Green—Pumping in adjacent well

Circle shows measurement point; flowmeter line shows general trend.
Negative numbers indicate downflow; positive numbers upflow.
Arrows show points of inflow or outflow to the borehole.

Figure 4. Borehole geophysical logs for well SBRW-2, Salem, New Hampshire, 2009.

Table 3. Depth of fractures, sampling depth, flow fractures, uranium concentrations, and flow-weighted uranium concentrations in well SBRW-2 for two pumping scenarios, Salem, New Hampshire, 2009.

[Samples were analyzed at the New Hampshire Department of Environmental Services Water Quality Laboratory; ft, feet below top of casing; µg/L, micrograms per liter; gal/min, gallon per minute; --, not calculated]

Dominant fractures (ft)	Zone investigated (ft)	Water sample depth (ft)	Borehole zone flow (cumulative fraction)	Sample uranium concentration (µg/L)	Flow-weighted borehole zone uranium concentration (µg/L)	Comment and primary flow zones
Scenario A. Sampling SBRW-2 while pumping 0.6 gal/min at the water surface in SBRW-2.						
		38	1.00	31		In casing, whole well
39					33	Inflow, base of casing
		41	0.45	28		
49, 78	41–120				31	Flow
		--	0.40	--		
126, 150, 160	120–170					Flow
		--	0.40	--		
220	170–252					
		252	0.40	31		
254	252–260				--	
		260	0.40	31		
265	260–270				3	
		270	0.35	35		
274	270–280				59	
		280	0.30	31		
283–284	280–307				19	Large fracture (283–284), flow below fracture
		307	0.24	34		
304, 309	307–312					Flow
		312	0.11	--		
Well bottom						

Dominant fractures (ft)	Zone investigated (ft)	Water sample depth (ft)	Borehole zone flow (relative fraction)	Fracture uranium concentration (µg/L)	Uranium (µg/L)	Comment
Scenario B. Estimated flow-weighted borehole zone concentration and total uranium for well SBRW-2 assuming borehole sealed below 270 ft.						
39	Base of casing to 41		0.84	31	28	Whole well
		41				
	41–252		0.05	31		
		252				
	252–270		0.05	3		
		270				Assuming a seal at 270 ft

Limitations and Alternatives to the Methods Used

The efficacy of a borehole-modification solution to naturally occurring contaminants in a borehole depends on the specific hydraulic characteristics of the borehole, which, for water-supply wells installed in fractured-crystalline bedrock, is highly variable and unique from well to well. Because of the high cost of installing and maintaining treatment (including the disposal costs of potential treatment residuals), a modest investment in characterization to assess the potential for a borehole-modification solution may be justified. Although the wells investigated in this study showed either little variability in contaminant concentrations between fracture zones or had an insufficient number of transmissive fractures (within the same borehole) to allow for sealing one or more contaminated fractures, the approach for borehole characterization used in this study shows promise for application at other public-water systems with exceedances of naturally occurring contaminants. Even if a modification in a given borehole is not capable of reducing contaminant concentrations to below the MCL, a reduction in contaminant load would reduce the treatment costs by extending treatment media life, reducing the mass of residuals for disposal, and possibly reducing the design size of the treatment system. Decreased treatment costs could justify, therefore, the initial investment in borehole characterization.

A goal of the study was to establish an approach for borehole investigation that could be replicated at other fractured, crystalline-rock water-supply wells. The methodology used in this study was optimized to provide reliable data on fracture-specific flow and contaminant concentrations while being technologically and financially feasible for most water systems and (or) water-industry consultants. As the study progressed through the three water systems, it was determined that it was important to ensure (by adequate pre-sampling water removal) that ambient flows, while the pump was offline, had minimal impact on the subsequent sampling effort.

The borehole geophysical logs that were most useful to this study were caliper, fluid specific conductance and temperature, and optical televiewer. Other logs, such as natural-gamma radiation and electromagnetic conductance, may have been less useful but provided additional information and were worthwhile to collect while working at a site when the pump was removed from the well. Multi-parameter fluid logs required more effort than was worthwhile for this study, particularly if similar information could be gained from fluid temperature and conductance logs during ambient and low-flow pumping.

The approach for this study used borehole geophysics and sampling techniques analogous to low-flow sampling. Another characterization approach uses a tracer introduced at the surface with depth-dependant samples collected with the production well pump in place and withdrawing water near the bottom of the borehole (Izbicki and others, 1999). The tracer approach may also enable resolution of fracture-specific flow and contaminant concentrations and has the advantage of sampling actual withdrawal-well operating conditions without the effort and expenses of pump removal and borehole geophysical logging. However, the operating conditions common to withdrawal wells in fractured-crystalline bedrock in New Hampshire typically involve large drawdowns of tens to over one hundred feet, and several point (fracture-controlled) inflows above and below the resulting water level in the well. An additional complication with such low-yield wells is the unsteady flow conditions—heads continue to decline during pumping, and the pumping ceases when head declines reach a point close to the pump level in the borehole. Under large drawdowns and with inflows near the base of a borehole, the tracer approach would be unable to resolve differences between inflows above the water level and below the pump. Additionally, advancing a sampling device down a 6- or 8-in. borehole past pipe, pump cables, and other obstructions can be problematic. An ideal borehole setup for conducting a tracer-type characterization would consist of a fully screened rigid PVC stilling tube (with at least a 1-in. diameter) installed in the borehole to allow a sampler to be easily advanced down the borehole.

Time-dependent sampling and analysis is another, very simple, technique that warrants additional investigation, either as a screening method for future investigation sites or possibly as a non-treatment option for reducing contaminant inflows. Bedrock withdrawal wells in New Hampshire are typically cycled on, to fill a system's storage tank, and cycled off when storage is met or drawdown in the well is near the depth of the pump. In a low-yield, two-well system typical of the study area, one well may be operated at a time allowing the second well to recover. Of the sites investigated in this study, individual wells were generally operated for less than 12 hours a day. Using a time-dependant sampling approach, samples are collected over the course of a withdrawal-well pump cycle, with frequent samples collected during the initial pump-on period. This technique may require considerable sampling over the course of a pumping cycle but if successful could result in a considerable reduction of investigative efforts.

This technique may indicate contaminant variations that may occur in a unique hydrogeologic setting; for example, as a primary fracture zone with low-contaminant concentration is depleted, a secondary fracture zone with high-contaminant concentration may contribute a larger percentage of the water supply. Use of an optimized pumping cycle may provide a means to either limit inflows from certain fractured zones or to enhance contributions from other zones, such as allowing adequate recovery time for recharge from overburden sediments. Used as a screening approach, by monitoring water quality with time during a typical withdrawal cycle, this method may make it possible to detect variations in contaminant concentration that would indicate variable source concentrations with time, in the bedrock or bedrock and overburden aquifer, which could be exploited. If aquifer contaminant variability exists either between fractures or spatially within the same fracture zone, it is possible that optimized pumping could be used to maximize the volume of lower contaminant concentration water produced by the well and minimize water with elevated contaminant concentrations. This approach was tested at the Francestown site; however, arsenic concentrations showed little variability during the pumping cycle investigated. Every fractured-rock well system is unique, however, and this approach warrants further testing at additional systems because of its low cost and potential benefits if successful.

Summary and Conclusions

Bedrock borehole fracture, flow, and water-quality characteristics were investigated at three small public-supply wells in southern New Hampshire in 2008 and 2009 in cooperation with the U.S. Environmental Protection Agency and the New Hampshire Department of Environmental Services. The public-supply systems each served approximately 50 to 200 individuals and were under regulatory constraints for exceedances of the Federal and State drinking-water standards for arsenic or uranium. Arsenic and uranium are naturally occurring contaminants that affect bedrock water-supply wells in New Hampshire and parts of New England. The investigation was conducted to quantify the flow-weighted concentrations of arsenic or uranium in the supply wells and assess whether specific fracture zones, if sealed, would result in acceptable concentrations of these contaminants. The investigation used borehole geophysical logging and zone-specific water-quality sampling to characterize boreholes and provide estimates of flow-weighted contaminant concentrations within each borehole. The public-supply wells were selected from systems in New Hampshire that had contaminant concentrations that were slightly greater than regulatory limits (within about 20 percent), had accessible wells, had sufficient secondary well capacity and water storage to allow for periods where a well could be taken offline and the pump removed for borehole characterization, and the water-system owners or operators were willing to participate in this investigation. Investigation of groundwater flow and quality in fractured-bedrock wells is challenging because fracture characteristics at each site are unique and the particular flow characteristics and water quality vary considerably from borehole to borehole.

The bedrock supply well investigated in Francestown, New Hampshire, was 392 ft deep, and the arsenic concentration of the well water was 14 µg/L. The water from this well accounted for about 60 percent of the total water supply in the Francestown water system. The borehole had few water yielding fractures; 30 percent of the well yield originated from a fracture at a depth of 128 ft and 50 percent from a fracture at a depth of 222 ft below top of casing. Because the range (3–4 µg/L) in flow-weighted arsenic concentrations between fracture zones was small, the possibility of reducing whole-water arsenic concentrations by borehole modification was not feasible.

The bedrock supply well investigated in Londonderry, New Hampshire, was 400 ft deep and yielded water with a uranium concentration of 54 µg/L (well LBRW-2). Water from a second supply well (LBRW-1), located 50 ft away, had a uranium concentration of 26 µg/L. Well LBRW-2 contained numerous fractures, including one very large, near-horizontal fracture, spanning 1 ft, at 255 ft below top of casing. Analysis of flow in the borehole indicated that nearly all flow into this well was from fractures located at 129 ft (22 percent), 95 ft (53 percent), and 69 ft (25 percent) below top of casing. However, with the other well in the system operating (well LBRW-1), nearly all flow leaves well LBRW-2 at the fracture at 129 ft. Flow-weighted uranium concentrations ranged between 52 and 59 µg/L. With the large contrast in uranium concentrations between the wells and a distinct hydraulic connection between the wells detected at 129 ft, it was estimated that this fracture may contribute a considerable amount of the uranium measured in well LBRW-1.

The bedrock supply well investigated in Salem, New Hampshire (well SBRW-2), was 315 ft deep and yielded water with a uranium concentration of 32 µg/L in 2009. Water from a second supply well, located 45 ft away (well SBRW-1), had a uranium concentration of 30 µg/L. The supply well investigated had about 10 fracture zones along the borehole length, including a large fracture spanning 1 ft at 283 ft below the top of casing. However, more than 50 percent of the inflow to the well was at the base of the well casing, presumably from overlying unconsolidated sediments, and the individual fractures identified each contributed less than 10 percent of the total flow to the well. The two boreholes appeared to have a poor hydraulic connection. The flow-weighted uranium concentrations varied from 3 to 59 µg/L; however, given the low yield of some of the fractures, borehole modifications were not estimated to help alleviate contaminant concerns.

Characterization of groundwater flow and quality in the fractured-bedrock wells that are typical of New Hampshire, and much of New England, is complex. Bedrock water-supply wells generally have unique fracture and hydraulic characteristics that control the water quality and the prevalence of naturally occurring contaminants therein. This report presents the results of three different fractured-bedrock supply wells. At two of the systems, there was either not enough variation in contaminant concentration or not enough yielding fractures for borehole modifications to be a viable potential remedy to elevated contaminant contaminations. The conditions at one of the bedrock supply-well systems investigated, however, showed promise for improvement of supplied water by borehole modification.

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Appendix 1. Sampling time, depth, contaminant concentration, and field parameters for water sampled from wells in Francestown, Londonderry, and Salem, New Hampshire.

[Samples were analyzed at the New Hampshire Department of Environmental Services Water Quality Laboratory; ft, feet below top of casing; µg/L, micrograms per liter; °C, degrees Celsius; µS/cm, microsiemen per centimeter; mg/L, milligram per liter; --, not calculated]

Site	Date MM/DD/YYY	Time hhmm	Depth (ft)	Sample concentration (µg/L)	Temperature (°C)	pH	Specific conductance (µS/cm)	Dissolved oxygen (mg/L)	Sample comment
Francestown							Arsenic		
FBRW-1	10/8/2008	--	--	14.6	--	--	--	--	Supply pump and discharge line (whole well)
FBRW-2	10/8/2008	--	--	2.7	--	--	--	--	Supply pump and discharge line (whole well)
FBRW-1	10/23/2008	0915	84	22	6.8	8.1	121	1	Pump discharge line (whole well)
FBRW-1	10/23/2008	1345	84	21	9.1	8.4	123	1	Pump discharge line (whole well)
FBRW-1	10/23/2008	1545	84	24	9.2	8.4	124	0.9	Pump discharge line (whole well)
FBRW-1	10/23/2008	1000	135	20	6.5	8.4	128	--	Downhole sampler
FBRW-1	10/23/2008	1001	135	20	6.5	8.4	128	--	Split replicate (of sample above)
FBRW-1	10/23/2008	1130	180	19	7.7	8.4	126	--	Downhole sampler
FBRW-1	10/23/2008	1131	180	18	7.8	8.4	127	1	Sequential replicate (of sample above)
Londonderry							Uranium		
LBRW-1	5/5/2009	--	--	26	--	--	--	--	Supply pump and discharge line (whole well)
LBRW-2	5/5/2009	--	--	54	--	--	--	--	Supply pump and discharge line (whole well)
LBRW-1	6/17/2009	1630	30	53	12.6	6.7	652	1	Pump discharge line (whole well)
LBRW-1	6/17/2009	1730	30	54	12.3	6.8	644	1	Pump discharge line (whole well)
LBRW-1	6/17/2009	1830	30	54	12.5	6.8	649	1	Pump discharge line (whole well)
LBRW-1	6/17/2009	1830	60	54	15.1	6.78	634	--	Downhole sampler, in casing
LBRW-1	6/17/2009	1800	100	58	15.5	6.8	613	--	Downhole sampler
LBRW-1	6/17/2009	1801	100	59	--	--	--	--	Sequential replicate (of sample above)
LBRW-1	6/17/2009	1730	145	52	15.2	6.8	656	--	Downhole sampler
LBRW-1	6/17/2009	1600	200	54	14.6	6.9	610	--	Downhole sampler
LBRW-1	6/17/2009	1601	200	54	--	--	--	--	Sequential replicate (of sample above)
LBRW-1	6/17/2009	1545	300	54	14.4	6.9	633	--	Downhole sampler
LBRW-1	6/17/2009	1445	320	53	19.2	6.9	627	--	Downhole sampler
LBRW-1	6/17/2009	1930	380	50	--	--	--	--	Downhole sampler
Salem							Uranium		
SBRW-1	9/19/2009	--	--	30	--	--	--	--	Supply pump and discharge line (whole well)
SBRW-2	9/19/2009	--	--	32	--	--	--	--	Supply pump and discharge line (whole well)
SBRW-2	11/4/2009	1145	30	28	10.9	6.7	335	1	Pump discharge line (whole well)
SBRW-2	11/4/2009	1430	30	27	--	--	--	--	Pump discharge line (whole well)
SBRW-2	11/4/2009	1520	30	27	--	--	--	--	Pump discharge line (whole well)
SBRW-2	11/4/2009	1115	38	31	10.9	6.8	331	4	Downhole sampler
SBRW-2	11/4/2009	1140	41	28	10.6	6.7	332	1.3	Downhole sampler
SBRW-2	11/4/2009	1200	76	25	10.6	6.6	315	1.5	Downhole sampler
SBRW-2	11/4/2009	1230	157	29	10.4	6.69	351	5	Downhole sampler
SBRW-2	11/4/2009	1300	190	30	10.2	6.69	333	1.5	Downhole sampler
SBRW-2	11/4/2009	1330	252	31	10.1	6.68	340	3	Downhole sampler
SBRW-2	11/4/2009	1400	260	31	--	--	--	--	Downhole sampler
SBRW-2	11/4/2009	1415	270	35	9.5	6.69	347	1	Downhole sampler
SBRW-2	11/4/2009	1445	280	31	9.3	6.72	353	2	Downhole sampler
SBRW-2	11/4/2009	1515	307	34	9.9	6.71	354	1	Downhole sampler

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