Ground Water Monitoring&Remediation

Cautions and Suggestions for Geochemical Sampling in Fractured Rock

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Abstract

Collecting water samples for geochemical analyses in open bedrock boreholes or in discrete intervals of boreholes intersected by multiple fractures is likely to yield ambiguous results for ground water chemistry because of the variability in the transmissivity, storativity, and hydraulic head of fractures intersecting the borehole. Interpreting chemical analyses of water samples collected in bedrock boreholes requires an understanding of the hydraulic conditions in the borehole under the ambient flow regime in the aquifer as well as during sampling. Pumping in open boreholes, regardless of the pumping rate and the location of the pump intake, first draws water from the borehole and then from fractures intersecting the borehole. The time at which the volumetric rate of water entering the borehole from fractures is approximately equal to the pumping rate can be identified by monitoring the logarithm of drawdown in the borehole as a function of the logarithm of time. Mixing of water entering the borehole from fractures with water in the borehole must be considered in estimating the time at which the pump discharge is representative of aquifer water. In boreholes intersected by multiple fractures, after the contribution from the borehole volume has diminished, the contribution of fractures to the pump discharge will be weighted according to their transmissivity, regardless of the location of the pump intake. This results in a flux-averaged concentration in the pump discharge that is biased by the chemical signature of those fractures with the highest transmissivity. Under conditions where the hydraulic head of fractures varies over the length of the borehole, open boreholes will be subject to ambient flow in the water column in the borehole. In some instances, the magnitude of the ambient flow may be similar to the designated pumping rate for collecting water samples for geochemical analyses. Under such conditions, the contributions to the pump discharge from individual fractures will be a function not only of the transmissivity of the fractures, but also of the distribution of hydraulic head in fractures intersecting the borehole. To reduce or eliminate the deleterious effects of conducting geochemical sampling in open boreholes, a straddle-packer apparatus that isolates a single fracture or a series of closely spaced fractures is recommended. It is also recommended that open boreholes be permanently outfitted with borehole packers or borehole liners in instances where maintaining the hydraulic and chemical stratification in the aquifer is of importance. In a field example, a comparison of results from sampling in an open borehole and in discrete intervals of the same borehole showed dramatic differences in the concentrations of chemical constituents in the water samples, even though chemical field parameters stabilized prior to both open borehole and discrete interval sampling.

Introduction

Recently much emphasis has been placed on protocols used to collect ground water samples that are representative of the aquifer rather than an artifact of borehole conditions or the sampling procedure (Puls and Barcelona 1996; Unwin and Huis 1983). This has spawned the wide application of low-flow sampling. As described by Puls and Barcelona (1996), low-flow sampling involves the placement of a pump or intake tubing adjacent to the screened interval of a well and pumping at rates on the order of 0.03 to 0.13 gallon per minute (gpm), or less in lower permeability formations to minimize drawdown in the vicinity of the well. Pumping at low-flow rates is conducted to avoid disturbing solids that have accumulated in the well and mobilizing colloidal material in the formation. The placement of the intake tubing adjacent to the well screen is intended to avoid mixing aquifer water drawn through the well screen with water in the casing in an effort to minimize the volume of water purged from the well prior to achieving a representative sample of the aquifer water (Powell and Puls 1993). This advantage to low-flow sampling is particularly attractive at sites with contaminated ground water, where the disposal or treatment of water withdrawn from the aquifer is a costly concern. Puls and Barcelona (1996) also recommend other sampling protocols, such as using dedicated downhole equipment or placing downhole equipment a significant time prior to sampling to minimize the disturbance to the water in the casing prior to sampling. Bachus et al. (1993) recommend the use of inflatable packers to isolate a section of the screened interval of the well to minimize the effect of mixing with water in the casing and eliminate the mobilization of particulate material at the bottom of the well.

Successful collection of representative samples of aquifer waters using low-flow sampling, however, is dependent on a variety of site conditions (Puls and Barcelona 1996; Stone 1997; Seeve et al. 2000). Natural flow in boreholes results because the borehole acts as a high-permeability connection across horizons in the aquifer having different hydraulic heads. This effect has been demonstrated both in theory (Reilly et al. 1989) and in practice (Church and Granato 1996), even in relatively homogenous aquifers. When there is natural borehole flow, placement of the pump intake at a specific elevation does not guarantee that water will be drawn through the well screen immediately adjacent to the pump intake. Natural flow in boreholes also raises questions about the potential for cross-contamination of different horizons in the aquifer and whether a representative sample of aquifer water can ever be achieved. Even in boreholes where there is no natural flow, low-flow sampling does not guarantee that water is drawn into the well adjacent to the pump intake. Heterogeneity in aquifer properties over the length of the well screen will result in water being drawn preferentially through intervals of high permeability. Clearly, wells having short screens are advantageous in using low-flow sampling protocols (Puls and Barcelona 1996). Stone (1997), however, points out that any well screen connecting materials of different hydraulic properties or hydraulic heads should be considered "long."

Although it appears that low-flow sampling is best suited for short-screened intervals in relatively homogeneous formations, its application has been applied in many heterogeneous geologic settings, including fractured rock (McCarthy and Shevenell 1998). With the exception of those boreholes drilled explicitly for monitoring contaminated ground water, short open intervals are rare in bedrock boreholes. Bedrock boreholes are usually cased through overlying unconsolidated materials, and in some instances, the casing may extend into the bedrock so that a target interval in the bedrock or a specific geologic unit is hydraulically isolated. In most geologic settings, long open intervals in the bedrock boreholes (especially domestic and public supply wells) are the norm because of the uncertainty in finding permeable fractures of sufficient yield. Puls and Barcelona (1996) recommend the use of borehole packers in fractured rock to isolate intervals in conjunction with low-flow sampling.

Sampling with borehole packers is not a standard practice in boreholes drilled in fractured rock, because the installation of borehole packers can be costly and time consuming. Consequently, it may be tempting to forego the installation of borehole packers in fractured rock and collect water samples in open bedrock boreholes using recommended flow rates and techniques that have been applied successfully in screened wells in unconsolidated materials (Powell and Puls 1993). The purpose of this paper is to demonstrate that ambiguous interpretations of water chemistry can arise from the hydraulic conditions associated with collecting water samples in open bedrock boreholes and discrete intervals of boreholes intersected by multiple fractures. The paper is also intended to put forward suggestions for collecting water samples in bedrock boreholes where identifying the variability in the water chemistry with depth in the aquifer is of importance. Throughout this paper, examples of fracturing, hydraulic condition, and chemical sampling in bedrock boreholes are drawn from investigations conducted in the bedrock of the Mirror Lake watershed in the Hubbard Brook Experimental Forest, Grafton County, New Hampshire. An overview of the hydrogeology and scope of the investigations in the Mirror Lake watershed is not presented here, but is available in Hsieh et al. (1993), Tiedeman et al. (1997), Shapiro and Hsieh (1996), Johnson and Dunstan (1998), Shapiro et al. (1999), and Shapiro (2001a).

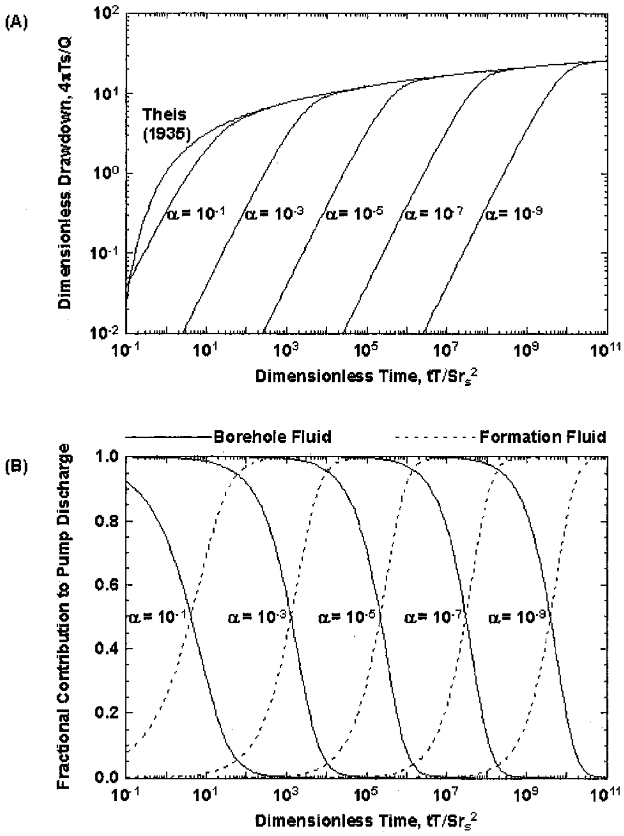

Figure 1. (a) Dimensionless drawdown and (b) the fractional contribution to pump discharge from borehole and aquifer water plotted as a function of dimensionless time and various values of α.

Cautions for Collecting Water Samples in Open Bedrock Boreholes

Borehole Volume

An open borehole is one in which a free water surface exists. Pumping an open borehole will initially draw water from the water in the borehole rather than the aquifer because the borehole acts as a high-permeability conduit in comparison to the permeability of geologic materials. Papadopulos and Cooper (1967) demonstrated the hydraulic response of pumping in an open borehole for an aquifer assumed to be homogeneous, isotropic, of infinite areal extent, of uniform thickness, and where the well screen fully penetrates the aquifer; their conceptual model is also applicable to a single, infinite fracture intersecting a borehole. A plot of the logarithm of drawdown in the borehole versus the logarithm of time initially shows a unit slope, which is indicative of water being withdrawn from the borehole rather than the aquifer (Figure 1a). In Figure 1a, drawdown and time are represented as dimensionless quantities, where the dimensionless drawdown is $4\pi Ts/Q$, the dimensionless time is tT/Sr_s^2, s is the drawdown, T is the aquifer transmissivity, Q is the pumping rate, t is time, S is the aquifer storativity, and r_s is the radius of the screened or open interval of the borehole. The drawdown in the borehole is also a func-

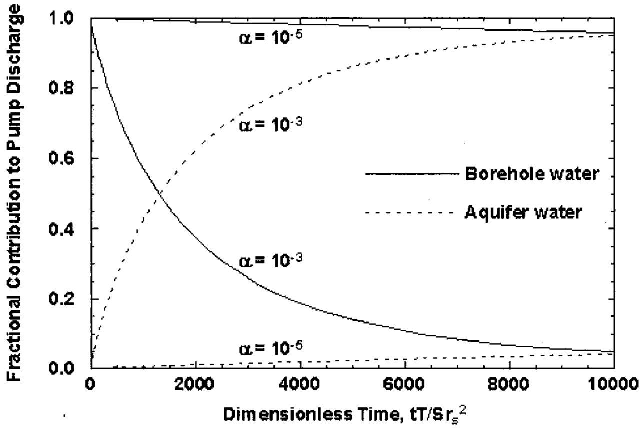

Figure 2. The fractional contribution to pump discharge from borehole and aquifer water plotted as a linear function of the dimensionless time for α equal to 10^{-3} and 10^{-5}.

tion of the dimensionless parameter $\alpha = Sr_s^2/r_c^2$, where α is the ratio of the storage in the aquifer per unit volume to the storage in the borehole per unit volume, and r_c is the radius of the casing. Also shown in Figure 1a is the drawdown in a borehole having an infinitesimal diameter (Theis 1935), which would result in water being drawn immediately from the aquifer at the onset of pumping. At late time, the hydraulic response in a pumped borehole of finite volume would overlay the response predicted for a borehole of infinitesimal volume.

The solution for the drawdown in an open borehole given by Papadopulos and Cooper (1967) can be used to quantify the time-varying contributions to the fluid volume in the borehole given by $Q_f + Q_b = Q$ (Barber and Davis 1987), where Q_f is the volumetric rate of water entering the borehole from the aquifer, and Q_b is the contribution to the pumping rate from the water in the borehole. The time-varying contribution from the aquifer to the borehole is $Q_f = 2\pi r_s T \left.\frac{\partial s}{\partial r}\right|_{r=r_s}$, and the contribution to the pumping rate from the borehole is $Q_b = \pi r_c^2 \frac{dw}{dt}$, where $\frac{dw}{dt}$ is the time rate of change of the water level in the borehole. In Figure 1b, the fraction of the pumping rate contributed from the aquifer and the borehole for various values of the dimensionless parameter α is plotted as a function of the dimensionless time. Figure 1b shows that the fractional contribution from the aquifer is initially small and gradually approaches unity only after the time at which the hydraulic response in the pumped borehole resembles that of pumping in a borehole of infinitesimal diameter.

Recommendations for sample collection are often based on the stabilization of chemical parameters (for example, pH, specific conductance, and temperature) measured in the discharge water. During the collection of chemical samples, however, the stabilization of chemical parameters may not correspond to the time at which aquifer water dominates the pump discharge from an open borehole, especially if chemical parameters of the borehole water are similar to those of the aquifer water (Reilly and Gibs 1993). In addition, if values of field parameters or concentrations of chemical constituents in the discharge water are plotted as a linear function of time (rather than a logarithmic function of time, as shown in Figure 1b), they may appear to have stabilized and be representative of aquifer water, whereas in actuality, the discharged water is a mixture that may still have a significant contribution from the borehole water. Results given in Figure 1b are plotted as a linear function of time for various values of α (Figure 2). In Figure 2, changes of a few percent over a linear time scale may be misconstrued as a stable chemical signature of the aquifer water. The stabilization of chemical parameters during sampling should be monitored over a logarithmic time scale rather than a linear time scale; the dimensionless time at which the contribution from the aquifer water dominates the pump discharge is more distinct when using a logarithmic-time scale.

To illustrate the time that may be needed to reach the point where water entering the open borehole from the aquifer is approximately equal to the pump discharge, consider a borehole with a single, infinite fracture having a transmissivity of 93 ft^2/day intersecting a 0.5-foot-diameter open borehole. Because the logarithm of the dimensionless time at which the pumping rate is approximately equal to the contribution from the aquifer is a linear function of α (Figure 1b), for any value of α and for transmissivity equal to 93 ft^2/day, it takes approximately 0.5 hour for 99% of the pumping rate to be attributed to aquifer water. In the following discussion, t_f is referred to as the time at which 99% of the pumping rate can be attributed to aquifer water. For a single fracture with lower transmissivity, t_f increases; e.g., t_f would increase to 5 hours for a fracture with transmissivity equal to 9.3 ft^2/day.

The previous discussions illustrate the need to consider hydraulic responses from pumping in open boreholes as a means of corroborating the stabilization of chemical parameters in the pump discharge. Because low-flow sampling assumes pumping at flow rates that minimize drawdown, it may not be possible to measure the time-varying drawdown accurately to identify the point at which water levels in the open borehole are representative of aquifer responses rather than borehole storage. For the previous example, where transmissivity is 93 ft^2/day, the pumping rate is 0.026 gpm, and α is equal to 10^{-5}, the drawdown at $t_f = 0.5$ hour is approximately 0.07 foot. Consequently, water-level monitoring equipment sensitive to detect changes in hydraulic head approximately equal to 0.007 foot would be needed to characterize the time-varying drawdown prior to t_f. If drawdown cannot be accurately measured at low pumping rates, it may be necessary to conduct and interpret preliminary aquifer tests at pumping rates higher than would be used during chemical sampling to design the collection of water samples at much lower rates.

Borehole Mixing

The model of Papadopulos and Cooper (1967) defines the time-varying rate at which aquifer water enters the borehole, which is not necessarily the time at which the water from the aquifer enters the pump intake. The location of the pump intake and other considerations also need to be considered in identifying the time at which the pump discharge is indicative of aquifer water, e.g., assuming that there is a single permeable fracture in the open borehole and placing the pump intake immediately adjacent to that fracture would result in the

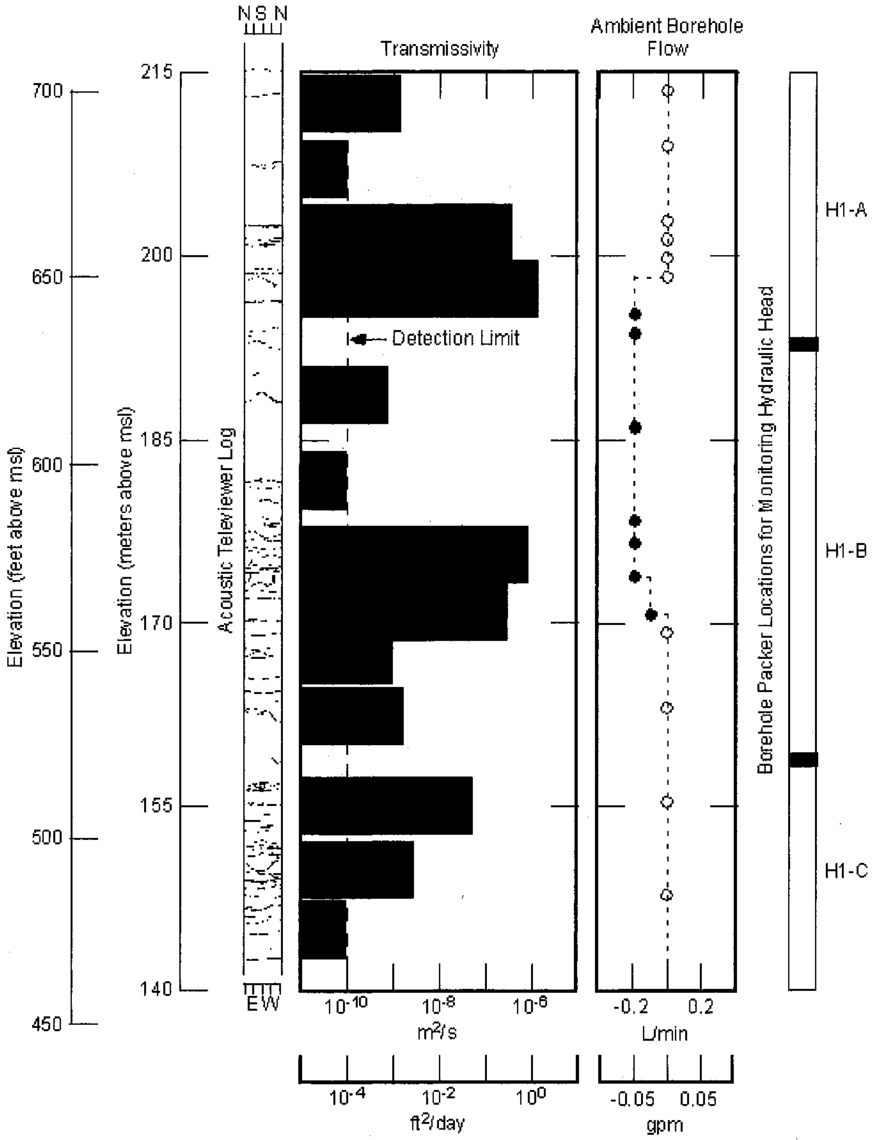

Figure 3. Transmissivity estimated from fluid-injection tests, interpretation of acoustic televiewer log showing fractures, ambient borehole flow, and the location of borehole packers for long-term monitoring of hydraulic head in borehole H1 near the Mirror Lake watershed in the Hubbard Brook Experimental Forest, Grafton County, New Hampshire.

pump discharge being composed of the aquifer water for $t > t_f$ (Powell and Puls 1993). For $t < t_f$, a mixture of water would be drawn from the borehole and the aquifer, even if the pump intake is placed adjacent to the permeable fracture. If the pump intake is placed at a location other than adjacent to the single permeable fracture in the open borehole, then borehole water would be mixed in the pump discharge for $t > t_f$, and a borehole mixing model would be needed to estimate the additional time necessary for the pump discharge to be representative of the aquifer water.

One example of a model of mixing aquifer and borehole water during pumping is where the borehole water and aquifer water entering the borehole are assumed to be well mixed (Robbins 1989; Robbins and Martin-Hayden 1991). Their model shows that the concentration of the pumped water approaches the concentration of the aquifer water as an exponential function of time. Assuming a concentration of one in the aquifer and an initial concentration of zero in the borehole, their model reduces to $C_w = 1 - \exp[-Qt/V_w]$, where C_w is the concentration of the pumped water, exp is the exponential function, and V_w is the borehole volume. This result implies that Qt/V_w must be approximately equal to 4.6 for the concentration of the pumped water to be within 1% of the concentration of the aquifer water. In this model, the purging time is directly proportional to the volume of water in the borehole; however, this purging time should be added to the time necessary for the aquifer water to dominate the pump discharge, as defined by the model of Papadopulos and Cooper (1967). Barber and Davis (1987) discuss the combination of a well-mixed borehole with the hydraulic model of pumping in an open borehole given by Papadopulos and Cooper (1967).

In situations where multiple fractures intersect a borehole, the pump intake will not be immediately adjacent to all fractures producing water in the borehole. Thus, the procedures and results of investigations that have shown minimal mixing between aquifer water entering the borehole and the borehole water are not applicable. In these situations, mixing between borehole water and aquifer water will occur for $t > t_f$, and a borehole mixing model is needed to estimate the time at which the pump discharge is representative of the aquifer water. Additional discussion of hydraulic conditions arising from multiple fractures intersecting the borehole is given in the following section.

Identifying the time at which a water sample in the pump discharge is representative of the aquifer water entering the borehole is complicated by factors other than borehole mixing. The density of the aquifer water entering the borehole relative to the density of the borehole water is likely to have an impact on the time necessary for the pump discharge to be representative of the aquifer water. Ground water that is denser than the borehole water may not be drawn into the pump intake, even if the pump intake is immediately adjacent to the permeable interval in the borehole. Also, there is no guarantee that a well-mixed model of the borehole water, as discussed in Robbins (1989) and Robbins and Martin-Hayden (1991), would characterize the mixing of a dense fluid in the borehole. The operation of the pump may also impact the mixing in the borehole and the time when the pump discharge is characteristic of the aquifer water. For example, several types of sampling pumps operate by cyclically withdrawing water and then momentarily stopping. The pulsing action of these pumps may result in inconsistent samples of water withdrawn from the borehole, especially if density differences between the borehole water and the aquifer water exist. Quantifying the effects of fluid density and pump operation in the borehole is beyond the scope of this investigation; however, such concerns must be addressed in designing a sampling protocol in bedrock boreholes by perhaps monitoring the stabilization of chemical parameters on a logarithmic time scale during pumping.

Multiple Fractures

In most bedrock terrain, it is unlikely that boreholes or even sections of boreholes used for chemical sampling will intersect only a single fracture. The frequency of fractures in bedrock depends on the rock type and the past and present local and regional stress fields. Johnson and Dunstan (1998) showed the frequency of fractures in rock consisting primarily of granite and schist to be approximately one fracture every 6.5 feet. These results from the Mirror Lake watershed were based on borehole logging in more than 30 bedrock boreholes, ranging in depth from ~200 to 1000 feet, over an area of ~1.5 square miles. An interpretation of an acoustic borehole televiewer log from borehole H1 near the Mirror Lake watershed, along with the transmissivity of discrete intervals of that borehole as a function of depth is shown in Figure 3. The acoustic televiewer log shows an opened and oriented view of fractures intersecting the borehole wall. The thickness of the line on the interpretation of the televiewer log is related to the exposed aperture of the fracture at the borehole wall. The transmissivity as a function of depth shown in Figure 3 was determined by isolating discrete intervals of the borehole using inflatable packers and conducting fluid injection or withdrawal tests in the packed-off interval (Shapiro and Hsieh 1998).

The aperture of a fracture at the borehole wall is not necessarily indicative of its hydraulic significance (Figure 3). Neither a large mechanical aperture, as interpreted from the acoustic televiewer, nor the density of fractures correlates with high transmissivity. Thus, identifying locations to conduct chemical sampling of aquifer water in bedrock boreholes cannot be based only on physical observations of the borehole walls. Identifying locations for chemical sampling in boreholes intersected by multiple fractures must be designed by synthesizing both geophysical and hydraulic information (Shapiro et al. 1999). The transmissivity of fractured intervals varies over many orders of magnitude over the length of the borehole and it is not a smoothly varying function of depth (Figure 3). Fractures having the maximum transmissivity may be located adjacent to fractures having transmissivity at or below the detection limit of the testing equipment. These properties will have a dramatic impact on the collection of water samples in bedrock boreholes.

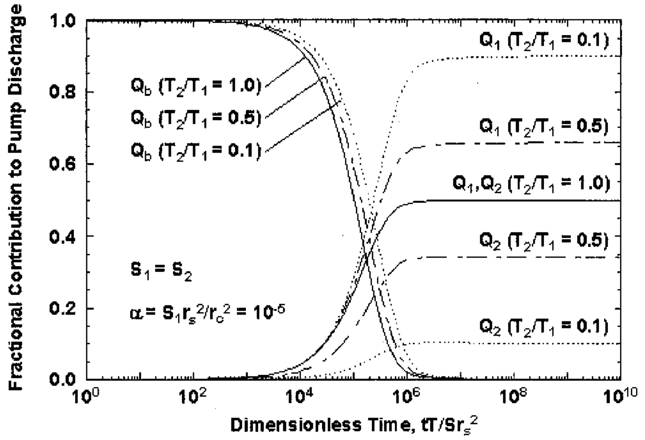

Figure 4. The fractional contribution to pump discharge from borehole water and two fractures intersecting the borehole plotted as a function of dimensionless time, for different ratios of T_1 and T_2, $S_1 = S_2$, and $S_1 r_s^2/r_c^2 = 10^{-5}$; T_1 and T_2 denote the transmissivities of the fractures, S_1 and S_2 denote the storativities of the fractures.

The hydraulic properties of the borehole also impact the contributions to the pump discharge. For example, assuming laminar flow in a cylindrical shaped borehole, an equivalent hydraulic conductivity of the borehole can be estimated using the Hagen-Poiseuille equation for laminar pipe flow (Reilly et al. 1989), i.e., $K_b = g \cdot r_s^2/8\nu$, where K_b is the effective hydraulic conductivity of borehole, g is the gravitational acceleration, and ν is the kinematic viscosity of the water. For example, a 0.5-foot-diameter borehole would have an effective hydraulic conductivity of 7.6×10^9 ft/day, which is at least five orders of magnitude greater than the most transmissive geologic materials, including fractures in bedrock aquifers (Freeze and Cherry 1979). Under such conditions, the fluid pressure response due to pumping in an open borehole will propagate first along the borehole and then along those fractures with the highest transmissivity. Consequently, the location of the pump intake becomes immaterial with regard to collecting water samples in a borehole intersected by multiple fractures. For example, pumping from a 0.5-foot-diameter borehole at a rate of 0.053 gpm would yield hydraulic gradients in the borehole of approximately 7×10^{-9} ft/ft; hydraulic gradients of such magnitude cannot be measured, and the hydraulic head over the length of the borehole would appear to be constant.

To quantify the effect of collecting water from fractures in boreholes intersected by multiple fractures of different hydraulic properties, the model of Papadopulos (1966) is considered here. Papadopulos (1966) considered a borehole intersected by two confined aquifers of different hydraulic properties, separated by impermeable rock; the confined aquifers are assumed to be homogeneous, isotropic, and of infinite areal extent. In this paper, the confined aquifers are assumed to be analogous to fractures intersecting the borehole. Wikramaratna (1984, 1985) developed a solution to this same problem that also included the effect of borehole storage. Wikramaratna (1985) showed the contributions of flow to the borehole for various hydraulic properties of two units intersecting the borehole. The time-varying fractional contribution from the borehole volume and from two fractures intersecting the borehole, where the transmissivity of the two fractures varies over an order of magnitude, is shown in Figure 4. As in the case of a single fracture intersecting the borehole, the early stages of pumping are dominated by borehole water contributing to the pumping rate. After the contribution from the borehole volume diminishes, the contribution to the volumetric pumping rate from the two fractures is weighted according to the transmissivity of the fractures intersecting the borehole. The storativity of the fractures influences the time at which the response in the borehole becomes more indicative of the aquifer responses rather than the borehole. Wikramaratna (1985) also illustrates other combinations of parameters and their effect on the contributions to pumping. For situations where there are more than two fractures intersecting the borehole, after the contribution from the borehole volume diminishes, the contribution to the volumetric pumping rate will be weighted according to the transmissivity of the fractures intersecting the borehole, regardless of their location relative to the pump intake.

If sections of a fluid-filled bedrock borehole are isolated using borehole packers, borehole storage would no longer be a factor affecting the pump discharge, and the model of Papadopulos (1966) can be used to investigate the effect of multiple fractures intersecting the borehole. As in the cases described previously, the contribution to the pump discharge will be weighted according to the transmissivity of the fractures intersecting the borehole, regardless of their location relative to the pump intake.

Pumping from an open borehole or an isolated section of a borehole intersected by multiple fractures results in flux-averaged water samples, where the contribution to the pump discharge from the concentration in each fracture is weighted by the transmissivity of that fracture. Thus, the concentration in the pump discharge will be biased by the chemical signature of those fractures with the highest transmissivity. For the transmissivity distribution shown in Figure 3, the discharge to a pump located in the open borehole will be dominated by two intervals, at elevations approximately 655 and 565 feet above mean sea level (amsl). Each of these intervals is approximately 30 feet in length; other fractures in the borehole will contribute less than 10% to the discharge of the pump. Without knowledge of the chemical signature of the individual fractures, it is impossible to deconvolve the flux-averaged concentration and identify the chemical contributions of the individual fractures.

Ambient Borehole Flow

The previous discussions assume no ambient flow in the borehole water column due to differences in hydraulic head in fractures intersecting the borehole. If the borehole is uncased and connects geologic intervals of different hydraulic head, flow will occur in the borehole under unpumped conditions (Reilly et al. 1989; Silliman and Higgins 1990; Church and Granato 1996). The interval with the lowest hydraulic head will be subject to the continual injection of ground water from intervals intersecting the borehole with higher hydraulic head. In addition, the continual ambient "pumping" of intervals of high hydraulic head may cause the redistribution of dissolved constituents in the ground water flow regime.

Ambient flow in bedrock boreholes may also be attributed to the chemical composition of the ground water. Fluid entering the borehole with different density than the borehole water may result in flow in the water column of the borehole. In situations where the chemical composition of the ground water varies to the extent that the density of the ground water is affected, interpretations of fluid pressure measurements will need to consider the density of the ground water in evaluating the hydraulic head and the potential direction of ground water flow.

Ambient flow in the water column of boreholes in fractured rock has been measured in many investigations (Hsieh et al. 1993; Paillet 1998); for example, using a sensitive thermal-pulse flowmeter (Hess and Paillet 1990). Figure 3 shows ambient flow in borehole H1 near the Mirror Lake watershed (Paillet 1991). The points on the ambient borehole flow log denote locations where measurements of vertical flow in the borehole were taken and the dashed line indicates the interpretation of the measurements. The borehole measurements indicate there is downward (negative) flow of approximately 0.053 gpm (which in a 0.5-foot-diameter borehole equates to a velocity equal to approximately 52 ft/day) originating in the borehole at a fracture approximately 640 feet amsl; the downward flow ceases at a number of fractures at about 575 feet amsl indicating that flow exits the borehole at this location.

In low-flow sampling, pumping rates of 0.053 gpm are considered to be reasonable for collecting water samples. On the basis of the borehole logs shown in Figure 3, pumping at 0.053 gpm and placing the pump intake at the fractures at about 575 feet amsl would simply draw water moving downward in the borehole; it would not draw any aquifer water from the fractures at 575 feet amsl, because the borehole has a much higher effective hydraulic conductivity than the fractures. If the pump intake instead was placed slightly below the fractures at about 640 feet amsl, then pumping at a rate of 0.053 gpm would yield a sample of the aquifer water entering at 640 feet amsl. In fact, a grab sample (without pumping) taken from the water column just below this elevation would most likely be representative of the aquifer water in the fracture at this elevation, provided that the borehole was open a sufficient time to establish downward flow between the two intervals.

To further demonstrate the effect of ambient borehole flow on the collection of water samples, a numerical model was developed to quantify borehole flow coupled with flow in fractures intersecting the borehole. For each fracture intersecting the borehole, a finite-difference formulation is used for the one-dimensional equation of radial ground water flow to a borehole (Smith 1969). The hydraulic response in the borehole is coupled to ground water movement in the fractures by using a finite-difference approximation for the fluid mass balance in the borehole (Wikramaratna 1985). In the examples presented here, a 0.5-foot-diameter borehole is considered, where the

Table 1
Hydraulic Properties of Hypothetical Fractures Used to Demonstrate the Influence of Ambient Borehole Flow on Geochemical Sampling in Bedrock Boreholes Intersected by Two Fractures

Case	T_1 (ft²/day)	H_1 (feet)	T_2 (ft²/day)	H_2 (feet)	Q_1 (t = 0) (gpm)	Q_2 (t = 0) (gpm)	$h_{ambient}$ (feet)
1	93	0.164	93	0.00	0.059	−0.059	0.082
2	93	0.164	9.3	0.00	0.011	−0.011	0.149
3	9.3	0.164	93	0.00	0.011	−0.011	0.0015

T_1 and T_2 denote the transmissivity of fractures 1 and 2, respectively; Q_1 (t = 0) and Q_2 (t = 0) denote ambient flow from fractures 1 and 2, respectively prior to pumping; H_1 and H_2 denote the boundary hydraulic head at the radius of influence for fracture 1 and 2, respectively; $h_{ambient}$ is the ambient hydraulic head in the borehole prior to pumping; ft²/day is square feet per day; gpm is gallons per minute.

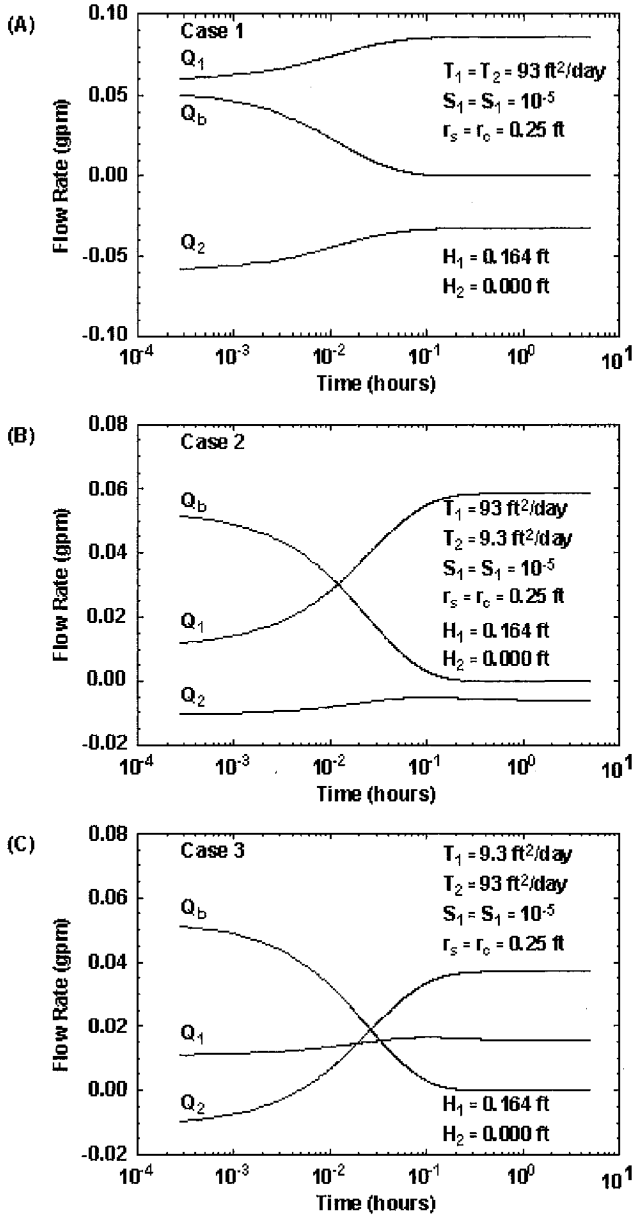

Figure 5. Flow rate from borehole water and two fractures intersecting a borehole assuming ambient borehole flow and the hydraulic properties listed in Table 1 for (a) case 1, (b) case 2, and (c) case 3.

hydraulic conductivity of the borehole is orders of magnitude larger than the transmissivity of the fractures. Hydraulic gradients in the open borehole on the order of 10^{-8} ft/ft are sufficient to drive borehole flow, and for the purpose of computations, the hydraulic head in the borehole is assumed to be constant over the length of the borehole. To achieve an initial steady-state flow in the fractures and simulate ambient borehole flow between fractures of different hydraulic head intersecting the borehole, the fractures are assumed to have a radius of influence equal to 16.4 feet, where the hydraulic head is assumed to be constant.

Three examples are chosen for illustration here. The examples involve two fractures intersecting a borehole where there is a difference of 0.164 foot in the hydraulic head between the two fractures; the ambient borehole flow resulting from this head difference is dependent on the values selected for hydraulic properties of the fractures. A summary of the cases used in this discussion is given in Table 1. Without losing generality, the hydraulic head in the fracture with the lower hydraulic head is always assumed to be 0 feet. Case 1 assumes the transmissivity of the two fractures intersecting the borehole to be the same and equal to 93 ft²/day. In cases 2 and 3, the transmissivity of the two fractures differ by an order of magnitude. In case 2, the fracture with the higher hydraulic head is assumed to have transmissivity equal to 93 ft²/day and the transmissivity of the fracture with the lower hydraulic head is 9.3 ft²/day. In case 3, the transmissivity of the fractures is opposite of that for case 2. In all cases, the storativity of the fractures is assumed to be the same and equal to 10^{-5}. Ambient borehole flow for case 1 is 0.059 gpm and for cases 2 and 3, ambient borehole flow is 0.011 gpm. For case 1, the ambient hydraulic head in the borehole is equal to the average of the heads in the two fractures (0.082 foot), because the two fractures have the same transmissivity. In cases 2 and 3, the ambient hydraulic head of the fracture with the largest transmissivity dominates the hydraulic head in the borehole (Table 1).

Figure 5 shows the results of pumping in an open borehole at a rate of 0.053 gpm for the cases considered in Table 1. The flow entering the borehole from the two fractures (Q_1, Q_2) is plotted as a function of time, along with the contribution from the borehole volume (Q_b). Negative flow rates associated with the two fractures in Figure 5 imply flow out of the borehole to the fracture. As discussed previously, the large contribution from borehole water during the initial stages of pumping diminishes with time, after which the contributions from the fractures can be calculated as the superposition of the ambient flow regime and the flow regime established in a borehole subject to no ambient flow. In case 1 (Figure 5a), ambient borehole flow (0.059 gpm) is greater than the pumping rate. Pumping in the borehole increases the flow rate from the fracture with the larger hydraulic head (Q_1); however, the pumping rate is not sufficient to eliminate the flow out of the borehole at the fracture with the lower hydraulic head (Q_2). Consequently, there is no contribution to the pump discharge from the fracture with the lower hydraulic head, even at late time. Although the fractures have the same transmissivity in this case, the ambient hydraulic conditions in the borehole affect the contributions from the two fractures, such that the fractures no longer contribute equally to the pump discharge.

In case 2 (Figure 5b), the fracture with the higher hydraulic head also has the larger transmissivity. In this case, the ambient borehole flow is smaller than the pumping rate; however, even after extended pumping there is still flow out of the borehole (Q_2) at the fracture with the lower hydraulic head (and transmissivity). In case 3 (Figure 5c), the fracture with the lower transmissivity has the higher hydraulic head. In this case, after the initial stages of pumping where the borehole volume dominates the pump discharge, the fracture with the higher transmissivity (and lower hydraulic head) produces the majority of water to the pump discharge. In cases 2 and 3, the total contribution from the fractures is no longer weighted by the transmissivity of the individual fractures. Consequently, under conditions of ambient borehole flow, it is necessary to know more than the distribution of transmissivity in the borehole to understand the contribution from various fractures.

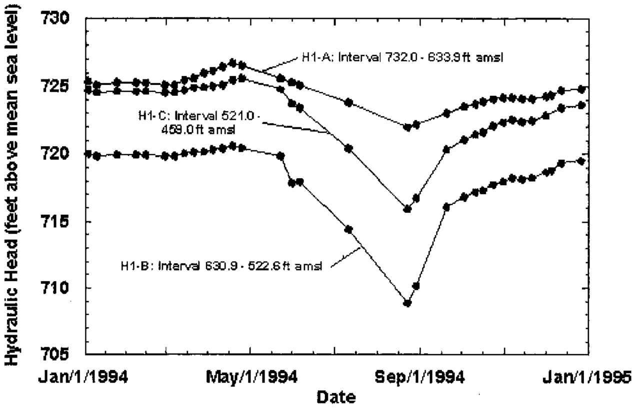

Figure 6. Hydraulic head of three discrete intervals in borehole H1 near the Mirror Lake watershed in the Hubbard Brook Experimental Forest, Grafton County, New Hampshire, January 1 through December 31, 1994.

Suggestions for Collecting Water Samples in Bedrock Boreholes

Long-Term Installation of Borehole Packers or Liners

In many fractured rock settings, poor connectivity of fractures and the relative low permeability of the host rock can lead to large vertical gradients in the hydraulic head between fractures separated by relatively short distances. Thus, in boreholes open to multiple fractures, ambient flow is often observed in the water column of the borehole. In those situations where understanding and maintaining the chemical and hydraulic stratification in the bedrock aquifer is important, it is necessary to eliminate ambient borehole flow through the use of borehole liners or inflatable or mechanical borehole packers (Johnson et al. 2001).

At sites where the ground water is contaminated, an open borehole with ambient flow may result in substantial contamination of parts of the bedrock aquifer that were previously uncontaminated (Williams and Conger 1990). Consider, as an example, the results from the flowmeter survey shown in Figure 3. Ambient vertical flow in the borehole H1 was approximately 0.053 gpm, which equates to 76 gallons per day. Flow entered the borehole at a fracture at approximately 640 feet amsl, was transported vertically in the borehole, and exited the borehole at a series of fractures at approximately 575 feet amsl. Placing packers or a borehole liner in a boreholes that has remained open for an extended period of time will eliminate the vertical hydraulic connection between fractures with different hydraulic head that intersect the borehole, but the chemical effects caused by the previously opened borehole will continue to have an impact after sections of the borehole have been hydraulically isolated. The long-term effect on the chemistry of water in the fractures intersecting the borehole, however, will depend on the duration the borehole remained open, the hydraulic and transport properties of the fractures intersecting the borehole, the ambient flow conditions in the formation, the primary porosity of the rock, and the capacity for diffusion into the primary porosity.

Even if the water chemistry of fractures intersecting an open borehole indicates no contamination, installing borehole packers to isolate intervals of different hydraulic head is advantageous in characterizing fluid movement and potential pathways for chemical migration in a bedrock aquifer. In the investigations of the bedrock in the Mirror Lake watershed, inflatable packers were placed in bedrock boreholes to monitor the vertical variability of hydraulic head for the purpose of developing an understanding of ground water flow in the bedrock (Hsieh et al. 1996). The packers also served to maintain the integrity of the chemistry of the ground water in the bedrock by isolating intervals of different hydraulic head. The packers were removed only when necessary to allow further hydrologic, geochemical, or geophysical testing.

The locations of the inflatable packers used for monitoring hydraulic head in borehole H1 are shown in Figure 3. The two packers installed in the borehole isolate three intervals, referred to as H1-A, H1-B, and H1-C (Figure 3), which are the uppermost, middle and bottom intervals in the borehole, respectively. The hydraulic head in these three discrete intervals in 1994 is shown in Figure 6. The uppermost interval (H1-A) had the highest hydraulic head in the borehole, whereas the middle interval (H1-B) had the lowest hydraulic head in the borehole, which is consistent with the measurement of downward ambient flow using the thermal-pulse flowmeter under open-hole conditions (Figure 3). The bottom interval of the borehole (H1-C) also has a hydraulic head above the middle interval; however, because of the low transmissivity of the fractures in the bottom of the borehole, upward flow was not detected with the thermal-pulse flowmeter (Figure 3) (the detection limit on the thermal-pulse flowmeter was approximately 0.01 gpm). Under open-hole conditions, fractures below 505 feet amsl also contributed to ambient upward flow, which exited the borehole at the fractures at approximately 575 feet amsl.

Packers were placed to monitor hydraulic head in discrete intervals of borehole H1 (Figure 3) on the basis of results from the thermal-pulse flowmeter, but additional hydraulic measurements were required to confirm the location of fractures with different hydraulic head. This was necessary because differences in hydraulic head between fractures intersecting the borehole may not yield ambient borehole flow that is above the detection limit of the flowmeter. Estimates of the ambient hydraulic head in discrete intervals in the borehole were determined as part of the hydraulic testing that defined the vertical distribution of transmissivity shown in Figure 3.

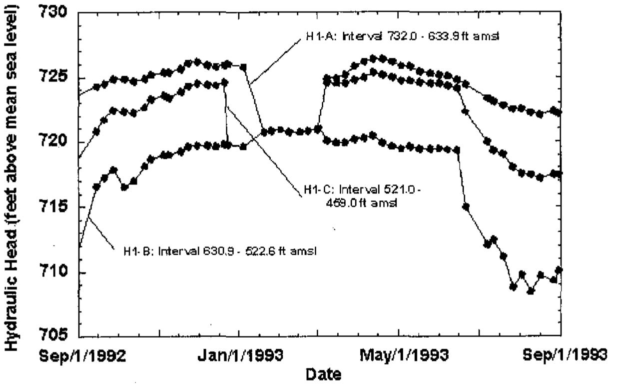

Figure 7. Hydraulic head of three discrete intervals in borehole H1 near the Mirror Lake watershed in the Hubbard Brook Experimental Forest, Grafton County, New Hampshire, September 1, 1992, through September 1, 1993.

Inflatable packers were used to isolate discrete intervals that were hydraulically tested (Shapiro and Hsieh 1998). In advance of injecting or withdrawing water from the test interval, the hydraulic head in the test interval was monitored and compared with the hydraulic head above and below the test interval. This information applied in conjunction with the interpretation of the thermal-pulse flowmeter survey was used to determine the placement of the borehole packers (Figure 3) for monitoring hydraulic head.

The measurements of hydraulic head in borehole H1 indicate a potential for downward flow from the shallow bedrock, and potential for upward flow from deeper in the bedrock (Figure 6). If a hydraulic head measurement was taken from an open borehole, the hydraulic head of the most permeable fractures would dominate the average hydraulic head measured in the open borehole. For example, Figure 7 shows the elevation of the hydraulic head of three discrete intervals of borehole H1 measured from September 1992 to September 1993. In December 1992, the lower packer in borehole H1 failed and intervals H1-B and H1-C equilibrated to a hydraulic head dominated by H1-B, because of the larger transmissivity in this interval. In January 1993, the upper packer in borehole H1 also failed, resulting in an open-hole hydraulic head that was a composite of the hydraulic heads of the three intervals. This composite hydraulic head was slightly larger than the hydraulic head in H1-B, because of the high hydraulic head and transmissivity in interval H1-A.

The equipment used to isolate intervals to stop ambient flow in the water column of the borehole and monitor hydraulic head could also be used to collect water samples, provided that the borehole volume of the isolated interval is minimized to avoid excessive purging of the borehole to collect a water sample that is representative of the aquifer water. In fractured bedrock, where the fracture porosity is small, withdrawing large volumes of water to purge the borehole may draw water from a huge volume in the formation, and the resulting water sample would not necessarily be indicative of the water in the fractures in the immediate vicinity of the borehole. The equipment used to monitor hydraulic head in discrete intervals of bedrock boreholes at the Mirror Lake site has continuous tubes extending from the hydraulically isolated intervals to above the top packer; direct water-level measurements were made in these tubes, and water samples could also be taken from these tubes (Hsieh et al. 1996). The isolated intervals for monitoring hydraulic head in borehole H1, however, were all longer than 65 feet (Figure 3). Consequently, water samples for chemical analyses from this and most other bedrock boreholes in the Mirror Lake area were not taken through the equipment used for long-term monitoring of hydraulic head. Instead, the water level monitoring equipment was removed and a separate apparatus was installed to isolate much shorter intervals in the bedrock borehole for the purpose of collecting water samples for chemical analyses (Shapiro 2001b).

Sampling Discrete Intervals in Bedrock Boreholes

A flux-averaged concentration obtained by collecting water samples from open boreholes or long-intervals of boreholes intersected by many fractures may provide a misleading picture of the distribution of chemical constituents in the ground water. For a better understanding of the distribution of chemical constituents in boreholes intersected by multiple fractures, the fractures should be hydraulically isolated during the collection of water samples. An apparatus to withdraw water samples from between two packers (a straddle-packer apparatus) is discussed in Shapiro (2001b). Using two packers to isolate an interval in a bedrock borehole for chemical sampling has two advantages: First, at the onset of pumping, water from the fractures enters the borehole at the same rate as the pumping rate, because the packers isolating the interval eliminate the affect of borehole storage; however, mixing between the aquifer water and the borehole water will occur and a borehole mixing model would have to be used to estimate the time needed to achieve a water sample that is representative of the water in the fractures. Second, using a straddle-packer apparatus, the distance between the borehole packers can be minimized, so that the volume of the isolated interval is reduced and the time needed to purge the isolated interval is also minimized.

In using a straddle-packer apparatus, it would be ideal to isolate a single fracture for chemical sampling; however, if the packer bladders are in contact with closely spaced fractures or a rough section of the borehole wall, packers may not form a suitable seal at the borehole wall. Therefore, it may be necessary to adjust the length of the packed-off interval to isolate closely spaced fractures intersecting the borehole, and consider the aggregated chemical signature of these fractures as a single permeable interval in the bedrock aquifer. In general, the optimal spacing of the packers for geochemical sampling will be dictated by borehole conditions and the location of permeable fractures.

In conducting chemical sampling using a straddle-packer apparatus, it is also advantageous to monitor fluid pressure between the packers, as well as above and below the hydraulically isolated interval (Shapiro 2001b). From the pumping rate and the fluid pressure monitored between the packers, the transmissivity of the isolated interval can be estimated (Shapiro and Hsieh 1998). Monitoring the fluid pressure above and below the packed-off interval will provide evidence as to whether the packers have sealed against the borehole wall, or if fractures in the isolated interval connect to the borehole above or below the packed-off interval. In either situa-

Table 2
Summary of CFC-12 Sampling in Bedrock Borehole H1 near the Mirror Lake Watershed in the Hubbard Brook Experimental Forest, New Hampshire

Sample ID	Sample Interval Elevation (feet amsl)	Transmissivity (ft^2/day)	Sample Date	Start Pumping	Pumping Rate (gpm)	CFC-12 Concentration					
						Sample 1		Sample 2		Sample 3	
						pg/kg	time	pg/kg	time	pg/kg	time
H1- Open 1991	684.4 – 459.0*	2.6 **	Aug. 12, 1991	11:15	0.53	174.0	13:01	163.2	13:29	168.3	15:10
H1-1-1991	656.8 – 641.7	1.3	Aug. 13, 1991	17:40	0.32	91.2	19:14	92.4	20:02	93.3	20:12
H1-2-1991	585.6 – 570.9	0.69	Aug. 13, 1991	14:30	0.98	83.0	15:14	75.3	15:54	73.3	15:59

*Denotes saturated section of the open borehole. The open borehole is 732.0 – 459.0 ft amsl; the water level in the borehole is below the bottom of the casing.

**Transmissivity of the open borehole is the sum of the transmissivities of the discrete intervals tested in the borehole (see Figure 3).

Note: Feet amsl is feet above mean sea level; ft^2/day is square feet per day; gpm is gallons per minute; pg/kg is picograms per kilogram water; time is sample collection time on the sampling date.

tion, the water in the pump discharge may not be representative of the aquifer water, as borehole water may be contributing to the pump discharge.

Sampling Discrete Intervals in Bedrock Boreholes: An Example

Water samples from bedrock boreholes in and around the Mirror Lake watershed in central New Hampshire were collected for analysis of chemical and isotopic composition and the concentration of dissolved gases (Shapiro 2001a). In all bedrock boreholes, water samples were collected using a straddle-packer apparatus similar to that discussed in Shapiro (2001b). In bedrock borehole H1 (Figure 3), samples for dichlorodifluoromethane (CFC-12) were collected in an open borehole and in packed off-intervals of the same borehole. CFC-12 is a synthetic gas that occurs in the atmosphere from the manufacturing of aerosols and other products. The historical record of CFC-12 and other chlorofluorocarbons (CFCs) in the atmosphere and their concentration in precipitation and ground water recharge has been used to determine the residence time of ground water in regional flow regimes (Busenberg and Plummer 1992; Dunkle et al. 1993). Because CFCs are detectable to about one part in 10^{15} parts water, they offer a particularly sensitive indicator of the contributions of mixing from various sources of different concentration.

Borehole H1 (Figure 3) was drilled and completed on July 16, 1991. Standard borehole geophysical logs, acoustic televiewer, and borehole flowmeter logs were conducted in the weeks immediately after drilling and the geochemical samples were taken on August 12-13, 1991 (Table 2). The borehole was left as an open hole during geophysical logging and up to the time that geochemical samples were taken. Consequently, the potential for the alteration in the natural water chemistry of the fractures with the lowest hydraulic head (for example, those fractures at approximately 575 feet amsl) must be considered in the interpretation of the geochemical analyses.

Prior to collecting samples from the open borehole and from packed-off intervals in borehole H1, the field parameters pH, temperature, specific conductance, and dissolved oxygen were allowed to stabilize in the pump discharge. During sampling in the open borehole, the pump intake was placed in the water column of the borehole below the bottom of the casing but above the most permeable fractures in the borehole. Drawdown was measured and interpreted during open-hole pumping to ensure that samples were collected after the effect of borehole storage diminished. During sampling of the discrete intervals isolated with borehole packers, the hydraulic head measured above and below the packed-off interval did not show a significant response during sampling to ensure that water was being withdrawn from the isolated interval in the borehole. Water samples for analysis of CFC-12 concentrations were collected according to procedures described in Busenberg and Plummer (1992). Three separate samples were taken and later analyzed in the U.S. Geological Survey CFC laboratory in Reston, Virginia, using a purge and trap gas chromatograph with an electron capture detector (Busenberg and Plummer 1992). The intervals sampled in borehole H1, pumping rates used during sampling, the time at which pumping started, the collection time of the sample, and the concentrations of CFC-12 in the water samples from the open borehole and the packed-off intervals are given in Table 2. The transmissivity of the open borehole and the two discrete intervals that were sampled are also given in Table 2. The two discrete intervals sampled constituted approximately 76% of the transmissivity of the open borehole.

Because of the exposed surface of the water column to the atmosphere and the disturbance to the water column caused by the emplacement of the sampling equipment, the concentration of CFC-12 in the water column of the open borehole prior to sampling was most likely near the atmospheric equilibrium concentration of CFC-12. In 1991 the concentration of CFC-12 in the atmosphere was approximately 501 parts per trillion volume (Busenberg et al. 1993). Using a water temperature in the borehole of 50°F and an atmospheric pressure associated with the land surface elevation at the borehole, the equilibrium concentration of CFC-12 in the water column of the borehole was calculated to be 323.3 picograms per kilogram (pg/kg) water (Busenberg et al. 1993).

The CFC-12 concentrations from the samples taken from the open borehole are approximately one-half the atmospheric equilibrium concentration at the time of sampling. The average CFC-12 concentration of the samples taken from the open borehole was 168.5 pg/kg (Table 2). In contrast, the average concentrations of the samples taken from the two packed-off intervals were 92.3 and 77.2 pg/kg, respectively (Table 2). Because the pump intake during open-hole sampling was located above the most permeable fractures and the volume of water pumped at the time samples were collected was significantly less than the volume of water in the borehole, the open borehole samples were most likely a mixture of the original borehole water and aquifer water moving up the borehole from the permeable fractures to the pump intake. Although the chemical parameters had stabilized during open borehole sampling and the drawdown in the borehole indicated that the borehole volume was no longer a significant component of the pump discharge, the CFC-12 concentration taken during open borehole sampling is significantly different from the CFC-12 concentrations from the discrete intervals. Placing the pump intake adjacent to one of the permeable fractures could have reduced this difference; however, the open borehole sample would still have been indicative of water withdrawn from multiple fractures in the borehole. In addition, a sample taken from the open borehole with the pump intake adjacent to one of the permeable fractures could still have a component of the original borehole water, because water would continue to move in the borehole from the most permeable fractures to the pump intake. Only after an extended period of time would the water column in the borehole be indicative of the aquifer water from the contributing fractures.

The two discrete intervals sampled in borehole H1 show different CFC-12 concentrations. This difference would not have been recognized if sampling was conducted only in an open borehole. The water sample H1-1-1991 (Table 2) is associated with the permeable fractures at approximately 640 feet amsl, and the water sample H1-2-1991 (Table 2) is associated with the permeable fractures at approximately 575 feet amsl. The fractures at 575 feet amsl have a lower hydraulic head and a lower CFC-12 concentration than the fractures at 640 feet amsl. The fact that the borehole remained open for approximately one month prior to geochemical sampling leaves open the possibility that there may have been an alteration in the water chemistry of the fractures at 575 feet amsl because of ambient borehole flow from fractures intersecting the borehole at 640 feet amsl and 505 feet amsl; the fractures at both elevations have higher hydraulic head than the fractures at 575 feet amsl. Therefore, it is likely that the CFC-12 concentration in the fractures at 575 feet amsl was elevated because of the higher CFC-12 concentration in the fractures at 640 feet amsl. In fact, the CFC-12 concentrations taken from H1-2-1991 (the fractures at 575 feet amsl) show a trend of decreasing concentration with time, which may be indicative of the purging of the water injected into this fracture while the borehole was left open.

Summary and Conclusions

Collecting water samples in open bedrock boreholes or hydraulically isolated sections of boreholes intersected by multiple fractures can lead to ambiguous interpretations of the ground water chemistry in fractured rock aquifers. In situations where it is important to characterize the spatial variability of the ground water chemistry in a bedrock aquifer, it is advantageous to collect water samples from discrete intervals that hydraulically isolate a single fracture or a group of closely spaced fractures in bedrock boreholes. Limiting the length of the hydraulically isolated interval reduces the time needed to purge the section of the borehole prior to collecting water samples for chemical analyses. Bedrock aquifers are usually characterized by small fracture porosity, thus, reducing the time needed to purge the borehole will reduce the volume of the aquifer that is impacted by pumping, and the water sample that is collected from the interval is representative of the aquifer in the immediate vicinity of the borehole. Monitoring the fluid pressure responses above and below the hydraulically isolated interval during pumping provides evidence whether the borehole packers have sealed against the borehole wall, or fractures in the packed-off interval connect to the borehole above or below the packed-off interval. Such information is crucial in identifying if the water sample is representative of the aquifer water or the borehole water. In addition, it is recommended that in situations where maintaining the chemical integrity of the bedrock aquifer is important, boreholes be outfitted permanently with borehole packers or borehole liners to reduce or eliminate the ambient flow that may occur in the water column of the borehole. Open boreholes that intersect multiple fractures act as high-permeability conduits that connect previously unconnected sections of the formation. Leaving boreholes open can result in the redistribution of chemical constituents and the potential contamination of previously uncontaminated sections of the aquifer. Monitoring the vertical variability in the hydraulic head in bedrock boreholes outfitted with borehole packers or borehole liners can also provide insight into potential pathways of ground water flow. The selection of locations for borehole packers to maintain the hydraulic and chemical integrity of the aquifer requires the synthesis of geophysical and hydraulic information to identify the location of fractures and their hydraulic properties.

In situations where water samples cannot be taken from hydraulically isolated intervals of limited length in bedrock boreholes, and water samples are collected from an open borehole, the effect of the water volume in the borehole must be considered in designing the collection of the water sample. At the onset of pumping in an open borehole, the pump discharge will be dominated by water from the borehole, regardless of the location of the pump intake, because the hydraulic conductivity of the borehole is orders of magnitude greater than the hydraulic conductivity of fractures. On the basis of results from Papadopulos and Cooper (1967), the time, t_f, at which water entering the borehole from the aquifer is approximately equal to the pump discharge can be ascertained by monitoring the logarithm of drawdown versus the logarithm of time. The time when stabilization occurs for chemical field parameters collected during pumping, however, may not correspond to the time, t_f, especially if chemical parameters of the borehole water are similar to those of the aquifer water. In addition, if the stabilization of chemical concentrations or field parameters in the pump discharge is monitored as a linear function of time (rather than as a logarithmic function of time), small changes in the concentrations of field parameters could be misinterpreted as a stabilization in the chemical signature, whereas in actuality, the pump discharge could still be a mixture that contains a significant component of the original borehole water.

Ground water samples collected by pumping from an open borehole or hydraulically isolated sections of a borehole intersected by multiple fractures yield a flux-averaged concentration in the pump discharge. The concentration of the water in the pump discharge is biased to the chemical signature of those fractures with the highest transmissivity. In situations where bedrock boreholes are used for domestic water supply, a flux-averaged concentration is a meaningful indicator of the water quality. In situations where it is important to delineate ground water contamination or the natural variations in ground water chemistry, the flux-averaged concentration cannot distinguish vertical variability in the water chemistry. Without knowledge of the fracture transmissivities and the concentrations associated with at least some of the fractures intersecting the borehole, the flux-averaged concentration cannot be deconvolved to determine the concentration of constituents in the individual fractures.

In instances where water samples are collected from boreholes intersected by multiple fractures with different hydraulic heads, ambient flow in the water column of the borehole occurs. If the rate of ambient flow in the borehole is of a similar order of magnitude as the pumping rate used for sample collection, then some fractures may not contribute to the pump discharge even though they may have a large transmissivity. The contributions to the pump discharge will depend on the transmissivity and the hydraulic head of the fractures intersecting the borehole.

In some instances it may be possible to obtain without pumping samples of aquifer water in boreholes that are subject to ambient borehole flow. For example, a fracture having the highest hydraulic head in the borehole will passively inject water into the borehole that will be distributed to fractures having lower hydraulic heads. Obtaining a grab sample in the borehole at the location of the fracture with the highest hydraulic head would yield a sample indicative of the water in that fracture. Although this may be viewed as an easy method of collecting water samples in bedrock boreholes, ambient borehole flow is of great concern at sites where ground water is contaminated or maintaining the natural variation in ground water chemistry is important. Also, collecting grab samples in bedrock boreholes does not address the collection of water samples from those fractures with the lower hydraulic heads in the borehole.

As an example of the ambiguity that may arise in collecting water samples from open bedrock boreholes, water samples were collected from an open borehole and from hydraulically isolated intervals in the same borehole; the bedrock borehole was located in the Mirror Lake watershed in the Hubbard Brook Experimental Forest, Grafton County, New Hampshire. In the openhole and discrete interval sampling, chemical field parameters were allowed to stabilize prior to sampling. The concentrations of dichlorodifluoromethane (CFC-12) in water samples from the open borehole were significantly different from the CFC-12 concentrations in the water samples taken from the discrete intervals in the borehole. The open borehole concentration of CFC-12 was most likely a mixture of the original borehole water and water from fractures entering the borehole during pumping.

Nomenclature

amsl = above mean sea level
C_w = concentration of pumped water
g = gravitational acceleration
H_1 = boundary hydraulic head in fracture 1 at the radius of influence in cases of multiple fractures intersecting a borehole
H_2 = boundary hydraulic head in fracture 2 at the radius of influence in cases of multiple fractures intersecting a borehole
$h_{ambient}$ = ambient hydraulic head in a borehole intersected by multiple fractures of different hydraulic head
K_b = effective hydraulic conductivity of a borehole
Q = pumping rate
Q_1 = flow rate from fracture 1 in cases of multiple fractures intersecting a borehole
Q_2 = flow rate from fracture 2 in cases of multiple fractures intersecting a borehole
Q_b = contribution from borehole volume to pump discharge
Q_f = contribution from aquifer waters to pump discharge
r_c = radius of the casing of the borehole
r_s = radius of the open interval of the borehole
s = drawdown
S = fracture storativity
t = time
T = fracture transmissivity
T_1 = transmissivity of fracture 1 in cases of multiple fractures intersecting a borehole
T_2 = transmissivity of fracture 2 in cases of multiple fractures intersecting a borehole
t_f = time at which 99% of pump discharge is derived from aquifer water
V_w = volume of pumped interval
α = ratio of storage in the aquifer per unit volume to storage in the borehole per unit volume ($\alpha = Sr_s^2/r_c^2$)
ν = kinematic viscosity of the fluid

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