Practical Single-Well Tracer Methods for Aquifer Testing

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Abstract

Conventional field methods such as pumping tests and gradient measurement are adequate for most water supply investigations, but do not yield sufficient information for modeling aqueous mass transport. Single-well tracer methods, when added to a program of conventional testing, can yield values for effective porosity, ground water flow velocity, and the vertical distribution of hydraulic conductivity directly from field data. New instruments, techniques, and interpretations render the single-well methods both cost-effective and accurate.

Introduction

There has been a great deal written describing the use of tracers in ground water studies. Microbes, organic dyes, radionuclides, gases, and a wide variety of soluble inorganic substances added to the ground water system have been so used. In environmental ground water monitoring programs, the pollutants themselves can be viewed as tracers. Where a difference in natural water chemistry exists between masses of water, the chemical characteristics themselves are useful as tracers, a prime example being the study of salt water intrusion into fresh water aquifers.

Tracers are generally classed as either *conservative* or *reactive*. A conservative tracer moves with the same velocity as the ground water, and its concentration is affected only by hydrodynamic dispersion. A reactive tracer, on the other hand, is affected by chemical or physical characteristics of the aquifer itself. Sorption to minerals, precipitation, inorganic oxidation or reduction, or biological activity can all serve to retard the mobility of a tracer or to reduce its concentration in the ground water.

For the purpose of characterizing ground water flow in aquifers, conservative tracers are by far the most useful. Using a reactive tracer generally adds to test results a dimension of complexity that defies interpretation. In the strictest sense, probably no perfectly conservative tracer exists, but several have been found to be quite satisfactory in hydrologic studies.

Bromide ion, introduced to an aquifer as the sodium, potassium, or lithium salt, is one of the more satisfactory tracers. Its conservative behavior is well-established in field studies, it is acceptable to environmental regulators in this application, it is easy to analyze in a ground water matrix, and it is foreign to fresh water (it is *not* foreign to sea water, which has a very consistent 65 mg/L bromide content). For the test methods discussed in this paper, bromide has been used exclusively as the tracer of choice.

A number of tracer test methods have been devised by hydrologists to interrogate aquifers. The simplest of these is to inject a tracer into a well, and to monitor one or more down-gradient wells by collecting and analyzing ground water samples. This multi-well approach to tracer testing can yield a direct estimate of ground water flow velocity. However, it has distinct disadvantages in terms of time, cost, and accuracy. First, it requires construction of one or more downgradient wells. Second, it requires prolonged periodic sampling and analysis. Third, the results of these tests are tracer breakthrough curves that are often (at least in the author's experience) indistinct and gradual, leading to ambiguous results.

Single-well methods have also been described. The *drift-and-pumpback test* and the *point-dilution test*, adaptations of which are the subject of this paper, were originally designed to yield an estimate of ground water flow velocity. Only one well, the test well, is needed, and the tests themselves require far less time and effort than multi-well tracer tests. To conduct a drift-and-pumpback test as described by Leap and Kaplan (1988), a tracer is introduced to the standing water column of the test well and allowed to drift, under natural gradient, away from the well bore. After a period of time, often a few days, the tracer plume is retrieved by pumping the test well. Ground water flow velocity is then calculated based on the amount of pumping needed to recover the tracer. It is intuitively obvious that the faster the ground water flow rate, the farther the tracer plume migrates and the more pumping required. The weakness of this test is that its interpretation requires knowledge of aquifer effective porosity.

The point-dilution test (e.g., Kearl et al, 1988) is conducted by introducing tracer to the water column (or a section of the water column isolated by packers) and by monitoring the rate at which the tracer concentration in the well bore decreases. The faster the ground water flow, the faster the tracer is swept from the well bore. The tracer is not recovered by pumping. This test also requires knowledge of effective porosity. In addition, it requires that a flow distortion factor for the well itself be determined.

Effective porosity, required for both tests, and the flow distortion factor required for the point-dilution test, have historically proven to be fairly elusive quantities in the practice of hydrology. As a result, single-well tracer tests have enjoyed no real advantage as alternatives to conventional field methods for aquifer testing, i.e., pumping tests and gradient measurement.

Of course, to determine ground water flow rate, field methods based on pumping tests and interpreted using Darcy's Law share a principal weakness with the single-well tracer methods - a value for effective porosity is needed. But at least the conventional methods don't require chemicals or chemical analysis in the field.

Recent work on single-well tracer methods has focused on combining tracer methods with conventional hydrologic test methods. Hall et al (1991) showed that by combining the drift-and-pumpback test with a conventional program of pumping tests and gradient measurement, both effective porosity and ground water velocity can be determined directly from test data. Hall and Raymond (1992) described a new method for conducting and interpreting the point-dilution test, and Hall (1994) showed that the point-dilution test can yield a vertical profile of aquifer hydraulic conductivity.

The following sections present step-by-step instructions for conducting and interpreting these tracer tests, including a description of new instrumentation and tools. The reader's basic familiarity with conventional field methods is assumed, and these methods are not described.

Tracer Injection

Both the drift-and-pumpback test and the point-dilution test require that the tracer be introduced quickly and evenly to the standing water column of the test well. The following simple displacement method has yielded excellent results.

a. Calculate and weigh the required amount of tracer salt (more about this in following sections).

b. Lower a hose of known inner diameter (ID) to the bottom of the well's screened interval. The hose must be open at both ends, and it will fill with well water. Black nylon flexible pipe (often used as Tremie pipe), PVC pipe joints, or even garden hose may be used. Hose ID of ¾ to 1 inch is usually most convenient. For best results (particularly for the point-dilution test), some sort of mixing device needs to be suspended from the bottom of the hose. A perforated plate of suitable diameter, suspended horizontally, has often been used. Excellent results have been obtained using a two-stage "static in-line mixer" commonly used in chemical process piping. A plastic jug, ballasted with gravel and fastened to the lower end of the hose with plenty of duct tape has proven surprisingly effective.

Whatever mixing device is chosen, it should be wide enough to provide effective mixing, yet not so wide as to get stuck in the well bore.

Calculate the contained volume of the hose ("volume A") from its lower end to the top of the standing water column or to the top of the screened interval, whichever is the lesser volume. In the latter case, also calculate the contained volume of the hose from the top of the screen to the top of the water column ("volume B").

Dissolve the tracer salt in distilled water (or a sample of ground water from the aquifer itself), such that the volume of tracer solution is equal to volume A. Where it has been necessary to calculate volume B, measure that volume of water and set aside for the moment (no tracer in this water).

c. *Slowly* pour the tracer solution into the top of the hose. If volume B is used, *slowly* pour it in next. (A funnel comes in very handy. Also, it is usually most convenient to cut the hose to extend just two or three feet from the top of the well.) Upon completion of this step, the hose will contain tracer solution from its lower end to the top of the test interval; water in the volume B section of the hose contains no tracer.

d. Pull the hose from the well. As it is raised, the tracer drains from the hose, and is mixed with the water in the well bore.

Instruments and Chemistry

The drift-and-pumpback test requires that tracer concentration be monitored during the pumpback stage. The monitoring has to be done in "real time", so analysis is required in the field. With a bromide tracer, this is best accomplished using ion-selective electrodes, which are available from several manufacturers. The point-dilution test requires *in situ* tracer measurements. Hall (1993) describes how to construct a submersible instrument suitable for measuring bromide tracer concentrations as deep as 100 feet in a well. This instrument is also based on ion-selective electrode (ISE) methods. A vastly improved version of the instrument, capable of measuring bromide (and other chemical parameters) at much greater depths is now commercially available.

All ISE instruments require calibration immediately prior to use. This in turn requires that a series of calibration standards be prepared, as follows.

a. Prepare a 10,000 mg/L bromide stock solution by weighing an amount of tracer salt as shown in the in Table 1. Transfer the salt to a 1 L volumetric flask and fill the flask about half-full with distilled water and dissolve the salt. Add more water while swirling the solution in the flask. Fill to the mark on the neck of the flask. Mix well by inverting the stoppered flask 20 times. Store at room temperature, out of direct sunlight.

b. From this stock solution, calibration standards that range in concentration from 1 to 1000 mg/L are prepared by serial dilution, using ground water collected from the test well. Using an accurate 100 mL graduated cylinder, transfer 100 mL of the stock solution to a second 1 L volumetric flask, add well water to the mark and mix as before. Transfer to a plastic 1 L bottle and label as 1000 mg/L.

Table 1

Lithium Bromide (LiBr)	10.868 g
Sodium Bromide (NaBr)	12.877 g
Potassium Bromide (KBr)	14.893 g

Thoroughly rinse the (second) volumetric flask and graduated cylinder with distilled water, and transfer 100 mL of the 1000 mg/L solution to the flask. Dilute, mix, transfer to a plastic bottle as before, and label as 100 mg/L. Two additional 10-fold dilutions will of course yield 10 and 1 mg/L solutions.

c. When calibrating the ISE instruments, start with the 1 mg/L solution. Pour enough of the solution into a beaker, cylinder, or other container suitable to hold the electrodes. Use a small amount of the solution itself to rinse the electrodes before placing them in the calibration vessel. Obtain a reading from the instrument per its operating instructions. Repeat with the 10, 100, and 1000 mg/L solutions.

The tracer salts listed in Table 1 are not considered hazardous; nevertheless, one should avoid ingestion or unnecessary skin contact. Also, the lithium salt is hygroscopic - it will absorb moisture from the air. Thus, accurate weighing of the salt can be frustrating in humid climes. The salts in Table 1 are interchangeable. That is, it is perfectly permissible to calibrate, for example, using sodium bromide and to conduct the field test using either of the other salts.

Drift-and-Pumpback Test

This test begins with careful planning. Of importance is the fact that the mathematics for its interpretation are designed for confined aquifers dominated by horizontal advection, and for fully penetrating wells. It can be successfully applied to unconfined aquifers if drawdown at the test well during pumpback is small (see below). The effects of partially penetrating wells is beyond the scope of this presentation. Drift time must be carefully chosen. If the tracer does not migrate sufficiently into the aquifer, results are biased. If the tracer drifts too far, it may not be possible to retrieve the tracer against natural flow.

The hydraulic conductivity and hydraulic gradient of the test interval must be known through conventional methods, and a reasonable range for effective porosity must be estimated. Most standard references on hydrologic testing offer some guidance in this respect. For best results, a few gallons of water from the test well should be collected for the purpose of preparing calibration standards. Store the water under refrigeration until needed.

Three test parameters must be chosen prior to commencement of the test. These are the amount of tracer needed, the elapsed time between tracer emplacement and commencement of retrieval pumping (i.e., drift time), and the pumping rate.

Experience has shown that approximately 3 g of bromide per lineal foot of test interval provides an excellent starting concentration. Calculate the amount of bromide needed, then multiply that mass by a factor to determine how much tracer salt must be weighed. For LiBr, NaBr, and KBr, the factors are 1.086, 1.288, and 1.489, respectively. Next, calculate the standing bore volume of the test interval in liters (this will correspond lengthwise to "volume A" calculated for tracer injection). Divide the amount of *bromide* to be used (calculated at 3 g per foot) by the volume in liters for the test interval, and multiply by 1000. This yields the nominal starting concentration in the well bore after tracer injection, in units of mg/L.

To calculate drift time and pumping rates, two formulae are required. The first is the form of Darcy's Law most useful to hydrologists, where

$V = KI/n$ (1)

and V is the average linear ground water velocity; K is the hydraulic conductivity; I is the hydraulic gradient; and n is the effective porosity.

The second is the formula presented by Hall et al (1991) for the solution to the drift-and-pumpback tests, where

$V = Qt/p\ bd2KI$ (2)

and Q is the pumping rate; t is the time elapsed from the start of pumping until the center of mass of the tracer has been recovered; b is the aquifer thickness (i.e., the test interval); and d is the time elapsed from tracer injection until the center of mass of the tracer has been recovered (i.e., drift time plus t). Unlike the solution presented by Leap and Kaplan (1988), Equation 2 does not require a value for effective porosity.

Using Equation 1 and a best estimate for effective porosity, calculate velocity. (If a range of porosities has been identified, also calculate velocity for high and low porosity.) From the velocity, calculate the amount of time needed for the tracer to move 8 feet, which is a convenient target value. Experience has shown that tracer movement of 6 to 10 feet into the aquifer yields good results. The result is the drift time to be used for the test.

Equation 2 is now rearranged to facilitate choice of a pumping rate, and

$Q = Vp\ bd2KI/t$ (3)

Let a target value for t be 1 hour. Add that hour to the drift time and use the sum as d in the equation. Using the velocity V calculated from Equation 1, calculate pumping rate Q.

For an unconfined aquifer, ensure that the pumping rate will not cause drawdown near the test well of more than 10% of the effective thickness of the test interval. This caveat is necessary because Equation 2 is strictly correct only for a confined aquifer. Experience has shown that 10% drawdown does not materially affect test results.

The time t does not signify the end of the test, rather, it is the pumping time required to recover one-half of the tracer originally injected into the test well. Ideally, pumping and monitoring should be continued until tracer concentration returns to background, and the entire tracer mass has been recovered. In practice, this is not always feasible, but a return to a tracer level of less than about 0.3 to 0.5 mg/L can be achieved with a reasonable pumping duration. In any case, the pumping campaign itself will usually have to continue for a period equal to 3 to 5 times t to develop a complete and useful recovery curve.

The test starts when the tracer is mixed into the well bore by removing the injection hose. (At this time, a submersible sensor can be used to conduct a point-dilution test - see below.) After the tracer has moved perhaps 2 or 3 feet, that is, after it has moved out from the well bore and into the formation, the pump can be set. A throttle valve will be needed to control and adjust flow rate, and a flow meter will be needed between the well head and the valve. In addition, a sampling tee and valve are required for sample collection.

When the pumping campaign begins, the effluent stream is immediately throttled to the chosen flow rate (flow rate should be checked and adjusted frequently - it will change with drawdown), and samples are collected and analyzed at five-minute intervals. Data should be plotted immediately to visualize the development of the tracer recovery curve, and to adjust the sampling frequency. That is, during periods of rapid change, sampling needs to be more frequent than during periods of gradual change.

Figure 1 illustrates a typical recovery curve. Over a period of approximately 4 hours, 23 samples were sufficient to define the curve. Note that the peak concentration was only 6 mg/L, but at this test site, the initial concentration in the 10-inch well bore was nominally 200 mg/L bromide. The farther the tracer drift, the smaller the tracer concentration in the effluent stream during recovery. Note also that in Figure 1, the center of mass of the tracer was recovered after 50 minutes of pumping, but that recovery of the entire tracer plume was not considered complete until 230 minutes of pumping.

To determine recovery time t, the recovery curve must be integrated. There are several ways of doing so. The method presented here is suitable for a calculator, or adaptation to a computer using a spreadsheet program, BASIC program, and so forth.

A total of m samples are collected and analyzed. The time that pumping starts is t0 and the time that the xth sample is collected is tx, so x ranges from 1 to m. The period of time in minutes represented by the xth sample is D tx, and is equal to (tx+1-tx-1)/2, except for the first and last samples, where the periods are calculated as (t1+(t2-t1)/2) and (tm-tm-1) respectively. With these definitions, the tracer mass recovered during the period represented by the xth sample is

Mx = D txCxQ/1000 (4)

where Mx is the tracer mass recovered in g; Cx is the tracer concentration in mg/L; and Q is the pumping rate in L/min. The cumulative sum of tracer mass recovered up to and including that recovered during the period represented by the xth sample is calculated as

CUMx = S M(1 to x)

Similarly, the total mass of tracer recovered during the test is therefore CUMm. This will be equal to the mass of tracer originally injected if the test is continued until the tracer concentration is effectively reduced to background level, sampling frequency is adequate, and field analysis is accurate. In practice, there is likely to be some difference between the injected amount and the calculated recovered amount. To compensate, the present mathematical analysis normalizes results to the calculated recovery.

At some time t, the cumulative sum of tracer recovered will be equal to one-half of CUMm, and t represents recovery of the center of mass of the tracer plume. It is unlikely that any single calculated CUMx will be exactly equal to ½CUMm, so t must be calculated by interpolation. Assume that CUMx < ½CUMm < CUMx+1. Therefore, tx < t < tx+1, and t is equal to the following expression:

tx+(tx+1-tx)(½CUMm-CUMx)/(CUMx+1-CUMx)

With t now known, Equation 2 is used to calculate the mean ground water seepage velocity, and Equation 1, rearranged as

n = KI/V

can be used to calculate effective porosity. These are mean values for the tested aquifer, and offer no vertical information.

Point-Dilution Test

This test was originally devised as a means to measure ground water flow rate, and in traditional application, usually only one interval at a time could be tested. As presented here, the test is used not to estimate velocity - that has been accomplished with the drift-and-pumpback test - but to develop a vertical profile of hydraulic conductivity using a single tracer application. In effect, *multiple, simultaneous* point-dilution tests are conducted by interrogating several test depths over time using a single submersible tracer sensor.

The ISE sensor is calibrated as described above using samples of ground water spiked with varying concentrations of bromide. The signal of the instrument is a voltage (measured in millivolts, mV) that is a linear function of the log10 of the bromide concentration over the range of interest, which for this test is from about 3 to 1000 mg/L bromide. For lesser or greater concentrations, there is some non-linearity, the reasons for which are beyond the scope of this paper. The relationship between bromide concentration and instrument response in mV is

$C = 10(E-I)/S$ (5)

where C is bromide concentration in mg/L; I is the ordinate intercept of a linear plot of mV *vs* the log of the bromide concentration; E is the mV response for the sample; and S is the slope of the linear plot.

Using the calibration data, calculate slope S by subtracting the mV response for the 10 mg/L solution from that of the 1000 mg/L solution, and divide the difference by 2 (note that the result will be a negative number equal to approximately -55). Then calculate the intercept I by subtracting S from the 10 mg/L mV response (subtracting a negative number *increases* I relative to the mV response from the 10 mg/L solution).

Kearl et al (1988) showed that, in a point-dilution test, the mean velocity v* of ground water through, and normal to the axis of, a well bore is

$v^* = -(V/At)\ln(C/C0)$ (6)

where V is the volume of the test interval; A is the vertical cross-sectional area of the test interval; t is time; C is tracer concentration at time t; and C0 is the initial tracer concentration. By differentiating Equation 6, and by substituting and rearranging, Equation 6 and Equation 5 are combined as

$dE/dt = kv^*$ (7)

where k is a constant. Thus, in a point-dilution test, velocity v*, at any given depth in a well bore, will be directly proportional to the slope of a linear plot of the instrument response in mV *vs* time.

Palmer (1993) showed that in a minimally developed well, v* is directly proportional to hydraulic conductivity, and that the proportionality constant is a function of well design. In this context, a minimally developed well is one that has not been pumped to such an extent that sediments outside the gravel pack have suffered differential development (e.g., *not* a heavily used production well). Thus, in a well that reasonably may be considered as minimally developed, the results of multiple, simultaneous point-dilution testing can be viewed as a vertical profile of hydraulic conductivity.

Hall and Raymond (1992) showed that for a heavily pumped - and heavily developed - well, the apparent contrast in hydraulic conductivity between highly conductive and poorly conductive zones is likely to be compressed. In either instance, however, the results of point-dilution testing as presented here are very useful in identifying the most productive zones in an aquifer.

The electrical cable used to deploy and operate the submersible bromide sensor needs to be marked so that the sensor can be suspended at chosen test depths. Adhesive PVC electrical tape of a contrasting color works well, and the well head itself serves as the bench mark.

Beginning shortly after the tracer has been injected into the well bore, lower the calibrated sensor to the shallowest test depth and obtain the instrument response in mV. Proceed downward, pausing at each depth to obtain a stable reading. Note the time at which each reading is obtained. Leave the instrument at the deepest test interval, and collect the next series of measurements working upwards, then downwards again for the next series, etc. Always raise and lower the instrument slowly, and with minimum agitation of the water in the well bore.

By minimizing the movement of the sensor, induced vertical mixing, which can bias results, is also minimized. The smaller the well bore, the more care must be taken.

At the start of the test, measurements should be collected at 10 to 15-minute intervals. The measurement interval can be later adjusted as appropriate. Plot the test results as mV *vs* time. Measurements may be discontinued when the data define a *linear* function at each measurement depth. Figure 2 illustrates the results of such measurements for twelve depths at a site where the ground water seepage velocity is approximately 2 ft/day (the same site represented in Figure 1). The point dilution test in this case was terminated after 5 hours.

Note that for the first hour, curvature is evident in the plots for some of the test depths. Hall and Raymond (1992) attribute this to initial non-ideal tracer distribution within the well bore and gravel pack. Further, the development of linear plots as the test proceeds is firm evidence for valid point-dilution results. The main conditions that can destroy the value of the results

are induced vertical mixing and vertical borehole currents (Hall, 1994). In both cases, plot linearity is also destroyed.

After the test is completed, the slope dE/dt of the straight-line part of the plot for each test depth must be determined. This can be done graphically or by linear regression. From Equation 7, it is seen that horizontal velocity v* through the well bore is directly proportional to dE/dt. Thus a *relative* vertical profile of v* can be constructed by normalizing each slope to the greatest measured slope. Figure 3 represents such a profile based on the field data represented in Figure 2. Figure 3 also includes a stratigraphic section based on the examination of drill cuttings. The flow profile and the stratigraphic section compare quite well. That is, most of the ground water flow occurs within a thick stratum of well-sorted sand.

If the criteria of Palmer (1993) are met, then a profile as shown in Figure 3 is also a profile of hydraulic conductivity. Because hydraulic conductivity is a strictly additive phenomenon, a value for the horizontal hydraulic conductivity for each test depth can be obtained using the following procedure.

Kearl et al (1988) show that

$v^* = Vna$ (8)

where a is the flow distortion factor for the point-dilution test. By combining Equation 8 and Equation 1, it is seen that

$v^* = KI/a$ (9)

Equation 9 relates v* to K for each test interval; it also relates the *mean* v* to the *mean* K for the test well. Mean K for the test well is of course known from pumping tests, and I is a constant. By calculating a mean v* for the well, factor a can be directly calculated. First calculate v* for each test depth, by applying Equation 5 and Equation 6 as follows.

A best-fit line for each test depth has already been established, as shown in Figure 2, to determine plot slope. Extrapolate the line to the beginning of the test (t = 0), ignoring any of the initial curvature. Determine the ordinate intercept (mV), and calculate the apparent concentration using Equation 5. This is C0 as used in Equation 6. For some time t near the end of the test, determine the mV response from the best-fit line. Calculate the concentration from Equation 5 and use the result as C in Equation 6, along with the time t. The quotient V/A in Equation 6 is equal to ½p r, where r is the well radius. A value for v* may now be calculated.

Repeat for the remaining test depths, then calculate the mean v* (note: unless the vertical interval represented by each test depth is the same, a weighted mean must be calculated). Using the mean v*, K, and I, calculate the flow distortion factor a using Equation 9. Factor a may now be used to directly calculate conductivity K for each test depth by using v* for that depth.

With a now known, other wells *that have identical construction to the test well* may be interrogated by point-dilution testing. If these other wells also meet Palmer's criteria, and if the local gradient I is known for the other wells, the result will be a vertical profile of conductivity K. Further, an average of the individual v* values (or a weighted average where necessary) can be used along with gradient I and factor a to calculate the mean hydraulic conductivity of the well by once again applying Equation 9.

Similarly, by multiplying the resulting mean value of K by aquifer thickness b, transmissivity can be estimated. Accuracy suffers compared to pumping tests, but the approach has already proven useful in the field as a very inexpensive method for rapidly screening a well field for the purpose of guiding and designing more rigorous tests.

Discussion

Ground water flow tracer tests for aquifer characterization have not been particularly appealing to practicing hydrologists for a number of reasons. Multi-well tests, conducted under natural gradient, have the potential to yield accurate values for ground water seepage velocity, but they can be very expensive and time-consuming to conduct. Further, unless monitoring wells are located precisely downgradient, test results can be ambiguous or even meaningless.

Single-well tests, in the past, have been presented as alternatives to conventional field methods for estimating ground water velocity, but have not offered any significant advantages over conventional stress tests. At a minimum, these tests required a best-guess estimate for effective porosity. In addition, they required equipment, instruments, and techniques that are probably unfamiliar to most hydrologists.

However, recent work as presented here has shown that by combining conventional hydrologic methods with single-well tracer methods, data yield and the subsequent accuracy of aquifer characterization is substantially enhanced. The effective porosity and ground water seepage velocity, as well as a vertical profile of hydraulic conductivity, can be derived directly from field data. The heretofore elusive flow distortion factor for the point-dilution test can similarly be obtained from field results.

Accuracy can be excellent. In a direct comparison between drift-and-pumpback results and those of a multi-well tracer test at a field site, Hall et al (1991) showed that accuracy was within 5% relative error for the measurement of velocity. Unpublished laboratory results (Istok, 1994) using an aquifer model showed an accuracy of 1.8% relative error for velocity measurement using a drift-and-pumpback test.

Similarly quantitative results are still lacking for the point-dilution test as presented here because of the expense of conventional depth-discrete testing methods, but semi-quantitative data presented by Newcomer et al (1996) indicate a very high correlation between point-dilution results and those of depth-discrete stress methods.

When conventional field methods are supplemented by tracer tests, both time afield and overall costs are obviously increased. Nevertheless, the increased data yield makes it worthwhile for the hydrologist to add tracer tests to his repertoire.

There are several areas of investigation where the additional effort to perform single-well tracer tests is justified. One such area is aquifer thermal energy storage (ATES), an energy conservation method where, for example, ground water is chilled during winter months using atmospheric heat exchangers, re-injected into the aquifer, and retrieved during summer months for use in air-conditioning (e.g., Hall and Raymond, 1992). It should be quite obvious that design of an ATES well field will depend on precise knowledge of the migration pattern of the stored thermal plume. ATES characterization requirements were in fact the impetus for developing the tracer methods presented here.

Tracer methods have also been extensively used at the Hanford Site, Washington, for detailed characterization of an *in situ* bioremediation demonstration site (Newcomer et al, 1995). Single-well methods were used for aquifer characterization, and recirculating forced-gradient tracer tests were used to elucidate nutrient flow-paths. The submersible bromide sensors used for point-dilution tests were also used for *in situ* monitoring during the recirculation experiments.

Sites where ground water is contaminated can benefit from tracer methods in two ways. First, accurate ground water migration rates can be established. Not only is this mandated by Federal environmental regulations, but it helps to support meaningful risk assessment. Second, monitoring wells can be rapidly screened using point-dilution methods, as noted above, to guide more rigorous testing using hydraulic stress methods. This helps to maximize the value of characterization data while minimizing unnecessary production of contaminated pumping wastes. In addition, the point-dilution methods can be used to identify the most productive zones within the contaminated aquifer. Sampling the productive zones yields the most representative results for the purpose of risk assessment.

The shape of the tracer recovery curve from the drift-and-pumpback test reflects the effect of dispersion on ground water flow. Recent (unpublished) experiments using particle-tracking computer codes to simulate ground water flow in drift-and-pumpback tests have been used to generate recovery curves. Results show that the curves are quite sensitive to the dispersion parameter. Thus, by matching generated curves to observed field data (e.g., Figure 1), a realistic dispersion parameter can be chosen for predictive computer modeling, at least on a local scale. The degree to which the dispersion parameter can be extrapolated to larger scales has not yet been tested in the field.

Hall et al (1991) described a recovery curve that was distinctly bimodal, and postulated (as one possibility) that the aquifer consisted of two main zones with distinctly different flow properties.

Particle-tracking simulation verified this possibility. That is, preferred flow paths may result in the development of more than one distinct plume, separated by depth, and moving at different rates - an interesting extreme of dispersion.

To date, success in the evolution of single-well tracer methods has depended upon the elimination of effective porosity as an unknown in the mathematical determination of ground water velocity from test data. The success is not quite complete, though, because depth-discrete values for hydraulic conductivity (from point-dilution) cannot be directly translated into ground water velocity. That is, while the *mean* effective porosity of the tested aquifer can be calculated from test data, the effective porosity at individual test depths remains unknown.

There is at least a partial solution to this problem that has been verified using computer experiments, but has not been tested in the field. Specifically, selective tracer emplacement can be used to interrogate a selected interval within an aquifer using the drift-and-pumpback method. For example, it would be of interest to test the 13- to 32-foot interval in the aquifer represented in Figure 3, because most of the aqueous transport occurs in that depth zone. By emplacing tracer across the zone, and by correcting the results of a drift-and-pumpback test to account for water produced from the rest of the aquifer, direct values for velocity and porosity could be calculated. The accuracy of the results would depend upon the accuracy of the hydraulic conductivity profile.

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(Figures not shown)

Figure 1. Bromide concentration *vs* time during the pumpback stage of a drift-and-pumpback test.

Figure 2. Bromide ion-selective electrode instrument response in mV *vs* time during point-dilution testing at twelve test depths.

Figure 3. Relative horizontal flow rate determined from point-dilution testing *vs* depth, compared to sediment stratigraphy.