

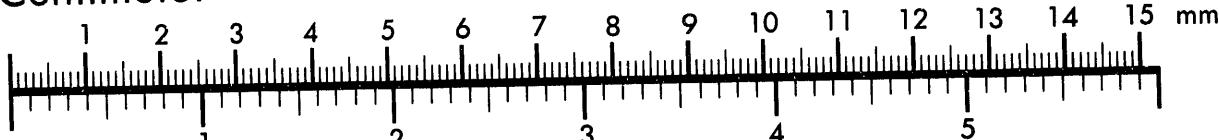


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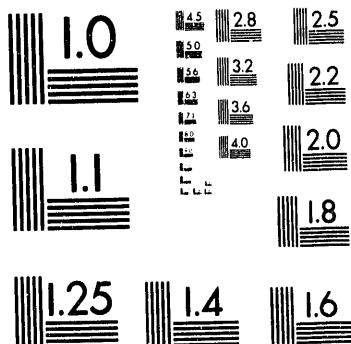
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APPLICATION OF GROUND WATER TRACER METHODS IN STRADDLE PACKER TESTING AT THE ICPP, INEL

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The State Oversight Program's straddle packer sampling system was tested at the Idaho National Engineering Laboratory during July-September, 1992, in USGS monitoring well #44. The straddle packer was designed for the Oversight Program's ground water research program, to provide a means of characterizing the vertical hydraulic and water quality variations believed to exist in the eastern Snake River Plain aquifer beneath the Idaho National Engineering Laboratory. During the field program, tracer introduction and recovery experiments were conducted to evaluate QA sampling objectives as well as to assess the feasibility of obtaining additional information on aquifer/borehole characteristics such as specific discharge through different aquifer zones, integrity of packer seals, etc.

A total of twelve tracer tests were performed on six different intervals from 467 to 600 feet below land surface (ft bsl). Lithium bromide powder dissolved in de-ionized water was used as a tracer. Br⁻ concentrations were monitored in the field with an ion-selective electrode, on discrete samples that were adjusted to constant ionic strength. The ion-selective electrode response was calibrated daily against Br standards that covered the working range. Precision and accuracy of Br⁻ measurements were determined from replicate analyses of standards and samples over the working concentration range and are both better than $\pm 4\%$ (2 sigma at 5 ppm Br).

All tracer tests were conducted in two phases: a) Emplacement - introduction of a slug of a known quantity of tracer, followed by continuous mixing within the test interval for periods ranging from 8 to 72 minutes (without pumping to surface), during which time the tracer was diluted by ground water advection through the test interval; and b) Recovery - pumping of the test interval to withdraw tracer from the borehole interval and the adjacent aquifer. Once tracer recovery had been completed, water quality sampling could be initiated, with the degree of interval purging having been defined by the degree of tracer recovery.

The initial concentrations of Br⁻ that were emplaced in the tests averaged 500 mg/l. An average of 95% of the Br⁻ that was emplaced in each interval was recovered during pumping, although in two tests only 22 and 59% of the emplaced tracer was recovered due to poor mixing conditions within the test interval during recovery, rapid advective loss into the aquifer during emplacement, and/or too short a pumping period.

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At the end of tracer recovery, and prior to water quality sampling, Br⁻ concentrations in the test interval ranged from approximately 1 to 8 mg/l above the 0.45 mg/l natural aquifer background. The highest residual amounts corresponded to intervals that were inefficiently purged during pumping or that were pumped for less than 30 minutes. Residual Br⁻ levels prior to water quality sampling can be used to define the proportion of sampled water that was not derived from the aquifer. However, due to the low levels of inorganic impurities in the LiBr powder (<100 ppm of other metals), the effect on measured water quality of such a small residual contamination would be undetectable for the major ions and would contribute sub-ppb levels of trace metals.

Tracer recovery data (natural log of dimensionless concentration vs time) from multiple tests on the 495-515 and one test on the 535-555 ft bls intervals are shown in Figure 1. These intervals were the only two that demonstrated adequate mixing within the borehole interval during the recovery phase, due to leakage across the packer valve designed to divert flow to the surface. The tracer concentration-time responses shown in Figure 1 are characteristic of a well-mixed volume in which the diluting solution (ie. ambient ground water) has a finite concentration of Br⁻. The response is characterized by a an initial, constant, semi-logarithmic rate of decrease of concentration vs time, followed by a decreasing rate of dilution and a final approach to a constant background value. A slight flattening of the curve at intermediate times indicates the return of tracer that had advected into the formation during the emplacement phase.

The return time of advected tracer as well as the apparent background Br⁻ concentration, C_b, was found to increase as longer tracer emplacement times were used, thus rendering the removal of tracer (plus borehole water) from the test interval more time-consuming due to the extensive advection and dispersion of tracer into the aquifer. The magnitude of this effect suggests that in a relatively low-hydraulic head interval which receives water from the borehole, pre-existing contamination of that zone by borehole water cannot be removed even by several hours of continuous purging. Therefore, it is doubtful whether water quality data on such intervals is representative of the ambient ground water at a distance beyond the borehole at that depth.

The effective volumes of the 495-515 and 535-555 intervals calculated from the initial rates of tracer dilution in the recovery phase (the slope of the straight lines) are shown in Figure 1. Other effective volumes are shown in Figure 2. The calculated volumes in intervals other than 495-515 and 535-555 were usually lower than the values estimated from caliper logs, although larger values were occasionally obtained. The wide range of apparent interval volumes shown in Figure 2 reflect inadequate mixing within the straddled intervals, indicating that little useful quantitative information can be extracted from the recovery phase data in all the two well-mixed tested intervals. The apparent tracer response and calculated apparent dilution volume that is obtained in any given interval is believed to depend on the position of fracture-controlled conduits supplying ground water inflow to an interval relative to the position of the pump intake.

Despite these problems the 1992 field data suggest that the analysis of tracer recovery data has promise as a technique for independently assessing aquifer characteristics such

as effective porosity and linear pore velocity, if adequate mixing can be maintained within the test interval. As shown in Figure 3, the tracer recovery data can be treated as a single-well tracer injection, drift and pumpback test by modelling the dynamic effects of pure borehole dilution and subtracting these effects from the observed concentration-time data. A methodology and theoretical basis for treating such data are currently being developed for future testing of this approach.

Due to inadequate mixing within the test intervals during the recovery phase of the 1992 tracer tests, subsequent discussion of tracer data in this communication is restricted to that obtained during the well-mixed emplacement phase. However, design modifications on the packer system are currently underway to provide the degree of mixing required to fully utilize tracer recovery data in future.

During the emplacement phase, the dilution rate of tracer in the test interval was calculated from the observed change in Br⁻ concentration between the time of emplacement and start of pumping. Since the interval was thoroughly mixed throughout the emplacement phase by using the pump to recirculate the interval fluid in a closed loop, a first-order dilution model describes the rate of tracer dilution with time:

$$C = (C^o - C_b)[\exp(-Ot/V) + C_b] \quad ,$$

where C^o is the initial Br⁻ tracer concentration in the borehole when the pump began purging the interval at time t=0, C_b is the background Br⁻ concentration characteristic of ground water in the aquifer, V is the volume of the test interval and O is the interval dilution rate, or rate of flow of ground water through the test interval. Thus, on a plot of ln(C) vs t, the slope of the initial linear portion of the response defines the interval dilution rate relative to the effective mixed volume, -O/V. Figure 4 shows the semi-logarithmic dilution rate of Br⁻ observed during multiple tests on the 495-515 ft bbls interval. The deviation of the 72 minute test (8/05) from the straight line shown in Figure 4 may be a consequence of the finite background Br concentration that is present in local ground water, or a reflection of non-ideal dilution conditions which may develop over long times in a fracture flow-dominated medium.

This simple first-order dilution model was used to interpret test results from the emplacement phase in all intervals. Interval volumes were calculated from the recovery data or estimated from the caliper log. Calculated interval dilution rates for all tests are shown in Figure 5. From estimates of the cross-sectional area of the borehole in each test interval, apparent specific discharge (= O/area) was also estimated and is plotted in Figure 5. Replicate determinations of dilution rate and specific discharge for the 495-515 interval are shown in Table 1, and provide an indication of the reproducibility that can be achieved with this borehole tracer method.

Specific discharge values calculated from these borehole dilution tests represent apparent values since they have not been corrected for flow field distortion around the borehole and so are higher than the actual specific discharge in the adjacent aquifer. Comparison of specific discharge values calculated from the 495-515 interval tests and

those estimated from Darcy's Law ($= K_{\text{horiz}} \times$ regional hydraulic gradient) indicates that the apparent specific discharges calculated from tracer dilution data appear to be high by approximately a factor of 3-4 (Table 1), indicating the magnitude of the borehole flow field distortion effect. This is within the range reported in the literature for the effect of borehole-induced flow distortion.

The profiles of interval dilution rate and apparent specific discharge appear to mimic the profile of hydraulic conductivity obtained by borehole flow meter logging in this hole (Figure 6; Morin et al., 1992), as would be expected if hydraulic gradients in all intervals were similar. However, as shown in Figure 6, the apparent hydraulic gradients obtained from the calculated specific discharge and hydraulic conductivity profiles, show a large increase with depth. Although the calculated hydraulic gradients are similar to regional gradients in the upper, high-permeability portion of the borehole, they are far too large in the lower part of the borehole where permeabilities are low. One possible explanation may be that the calculated specific discharge values in the deeper portions of the borehole are too high due to borehole-induced flow distortion, although the magnitude of such an effect would have to be far larger than any reported in the borehole dilution logging literature. An alternative possibility is that large vertical gradients may exist in the aquifer (as suggested by the high flow rates observed in this and nearby open boreholes during flowmeter logging; W. Bennecke and S. Wood, pers. comm., 1992 and unpubl. data), such that significant vertical flow is responsible for much of the observed tracer dilution in the lower test intervals.

References:

Morin, R., Barrash, W., Paillet, F. and Taylor, T. (1992) Geophysical logging studies in the Snake River Plain Aquifer at the Idaho National Engineering Laboratory: INEL Wells 44, 45, 46; USGS Water Resources Investigations Rept. 92-4184.

Table 1 - Tracer Dilution Rate Calculations in Interval 495-515 ft bls

Test Date	Calculated Dilution Rate ¹		Calculated Specific Discharge (in interval)		Estimated Specific Discharge (in interval)	
	liter/min	cm/min	ft/day	cm/min	ft/day	
7/21	15.86	1.19	56.2	0.35 ²	16.5 ²	
7/22	16.84	1.39	65.7			
7/23	14.73	1.10	52.0			
8/06	14.12	1.13	53.4			

Average

Dilution Rate = 15.39 l/min

RMS Deviation = 1.05 (6.8%)

Footnotes

1. Total ground water flux through the test interval, as calculated from observed tracer dilution during the emplacement phase

2. Estimated from Darcy's Law, assuming a regional hydraulic gradient of 0.0015 and a hydraulic conductivity in the interval of 11000 ft/day (3300 m/day), as determined by Morin et al. (1992)

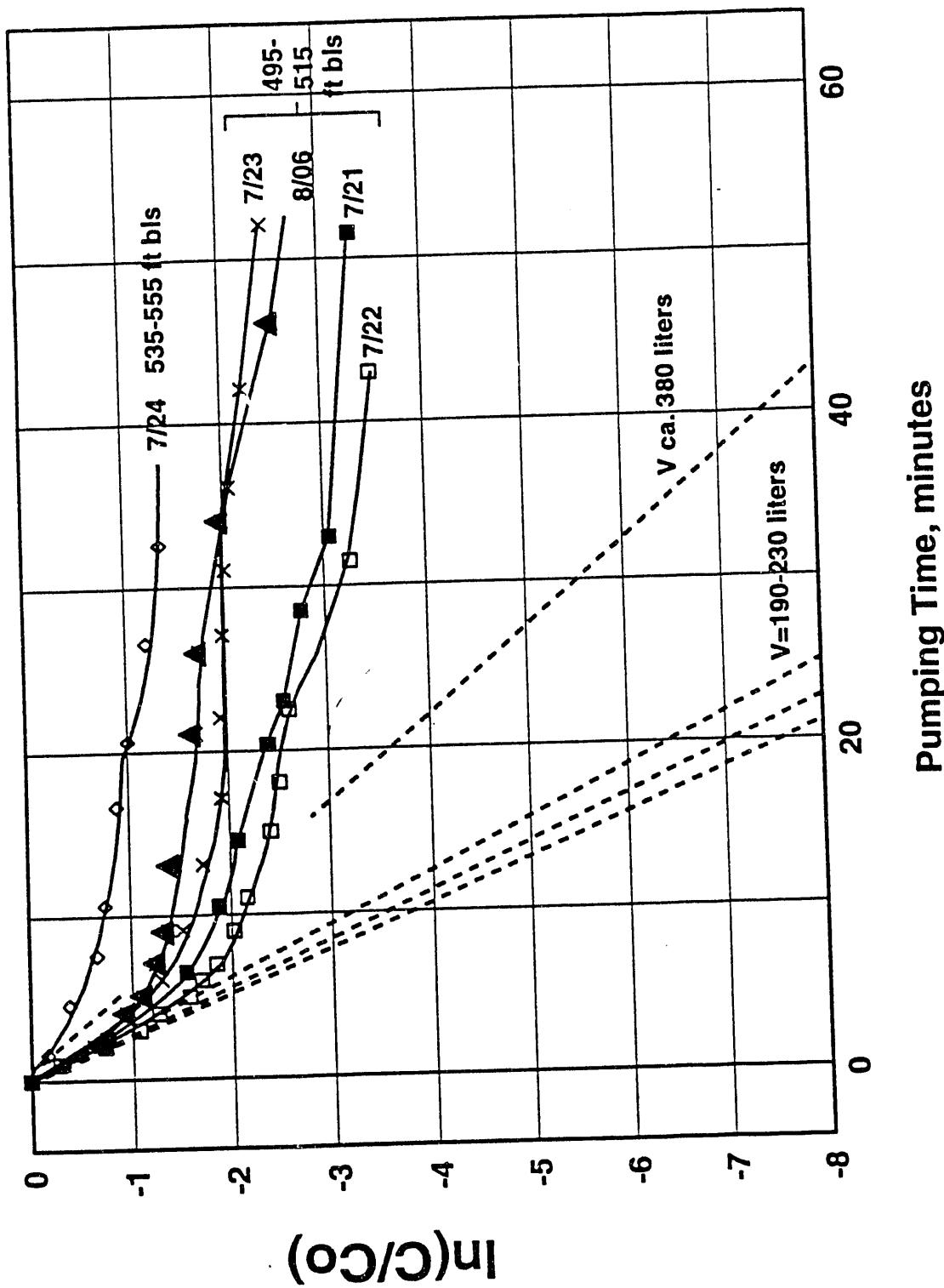


Figure 1. Examples of tracer concentration-time response during recovery phase in test intervals 495-515 and 525-555 ft lbs. Dashed lines represent initial dilution rates for several volumes shown.

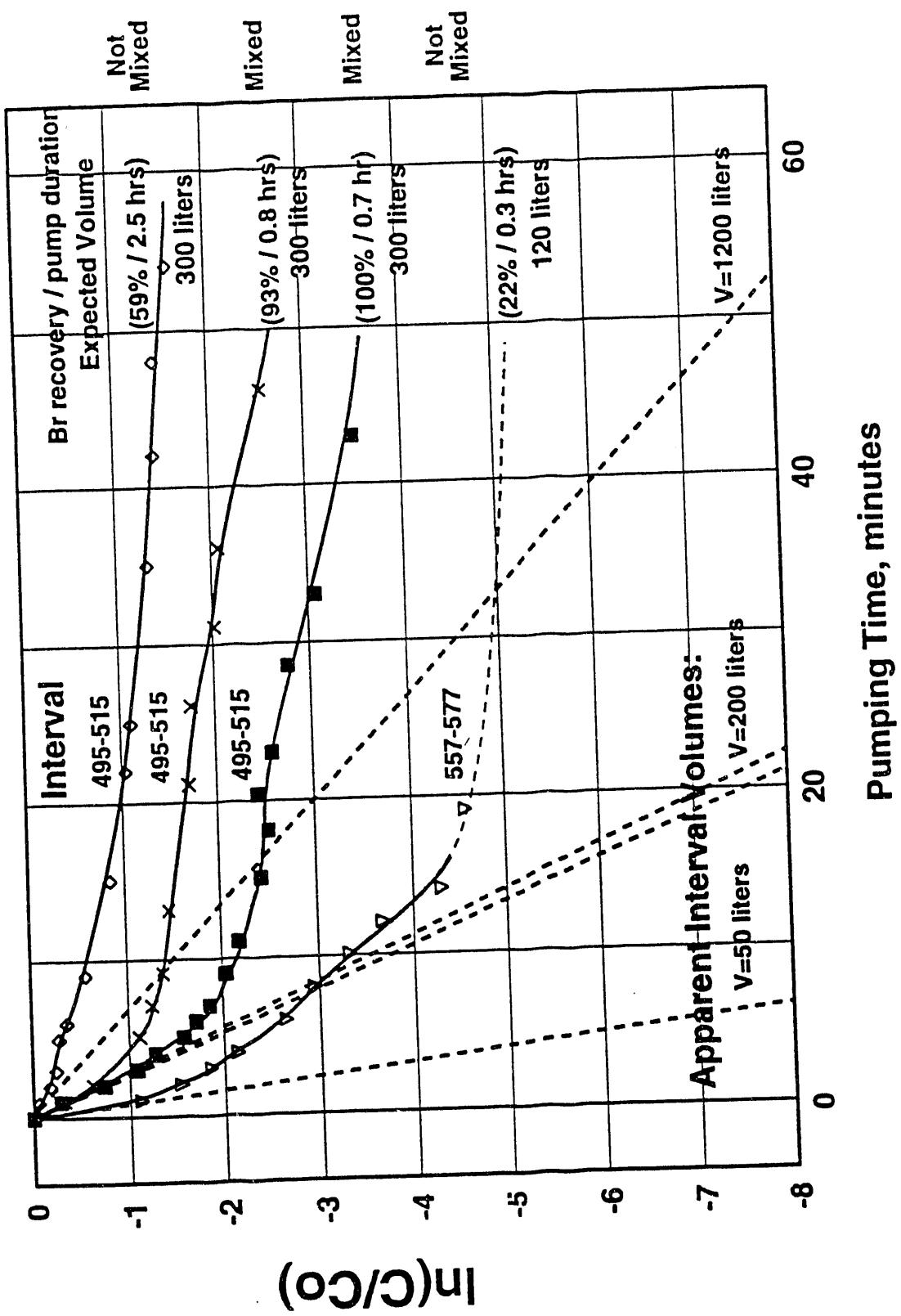


Figure 2. Characteristics of Br tracer recovery in various intervals showing the effects of different degrees of mixing on the effective dilution volumes. Note that apparent volumes calculated from initial rates of dilution (dashed line slopes) differ considerably from volumes expected from caliper logs, as shown on right of figure.

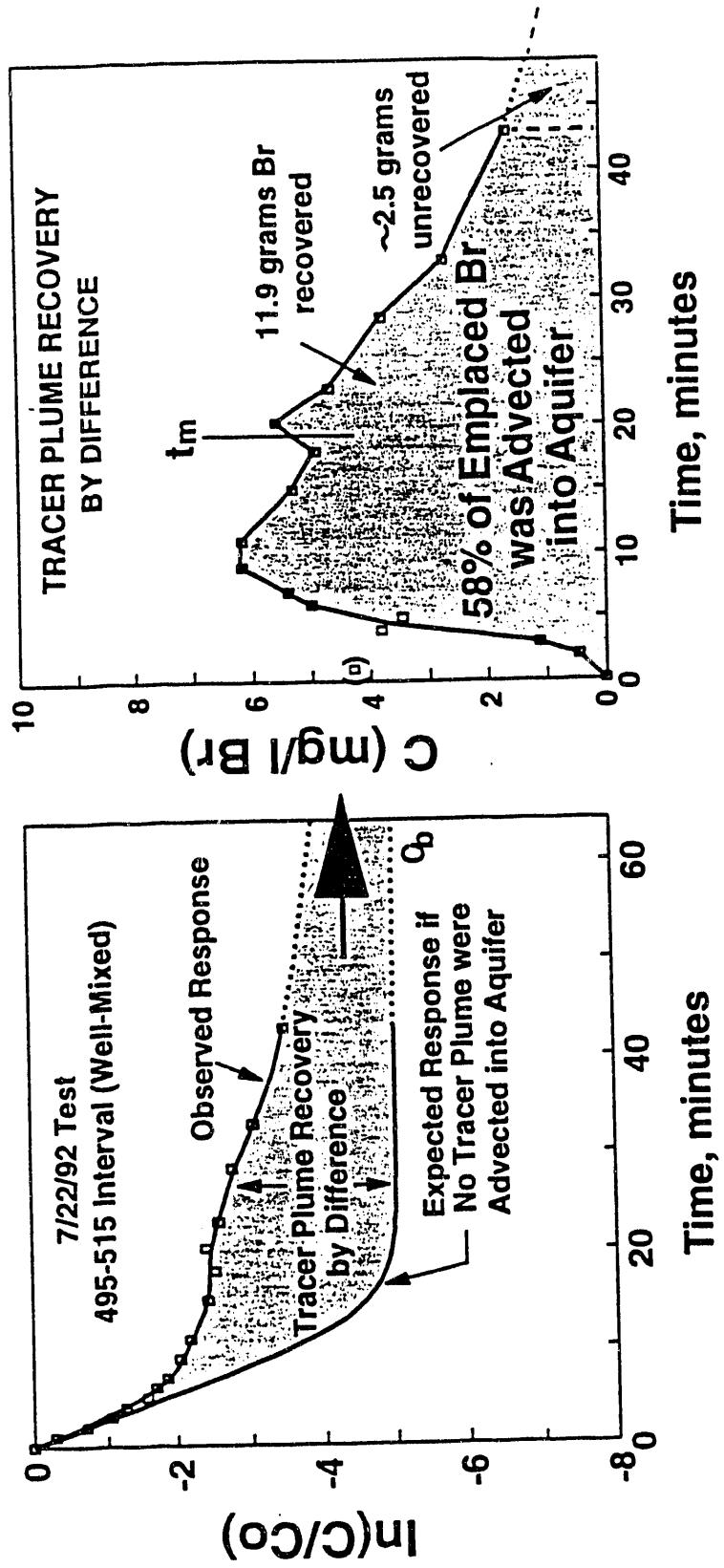


Figure 3. Proposed method for utilizing tracer recovery data in future. Tracer emplacement and recovery phases constitute a single-well injection, drift and pumpback test, wherein the mean two-way travel time of the advected tracer plume is a measure of linear pore velocity. In this test, estimated two-way travel time, t_m , is approximately 20 minutes or very close to twice the circulation time during the tracer emplacement phase.

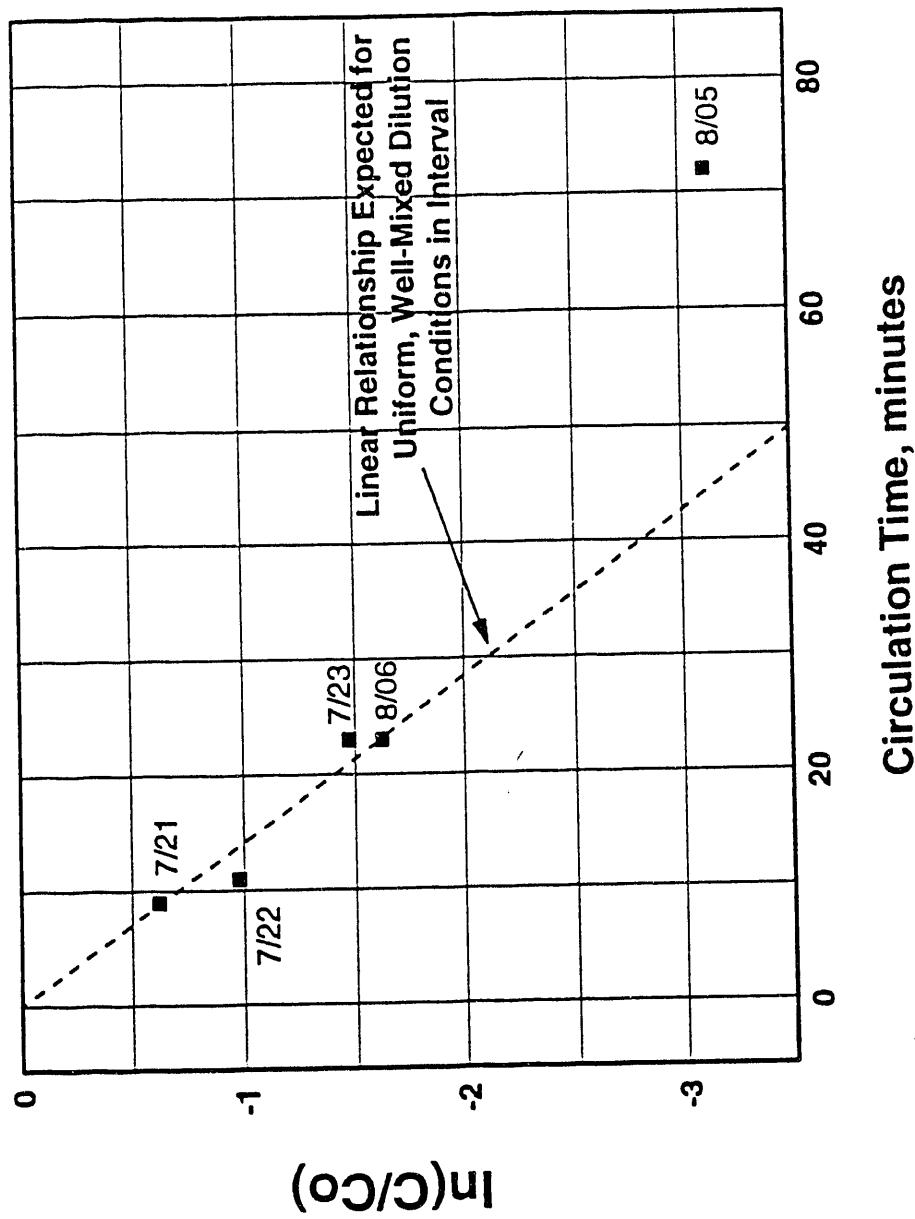


Figure 4. Dilution rates of Br tracer in replicate experiments on 495-515 interval, as calculated from emplacement phase data. Four of the five points fall along a straight line indicating that dilution within the interval can be described by a first-order dilution equation. The fifth point suggests that background Br is affecting the dilution process or that non-uniform dilution due to fracture-controlled flow is becoming progressively more important over longer dilution times.

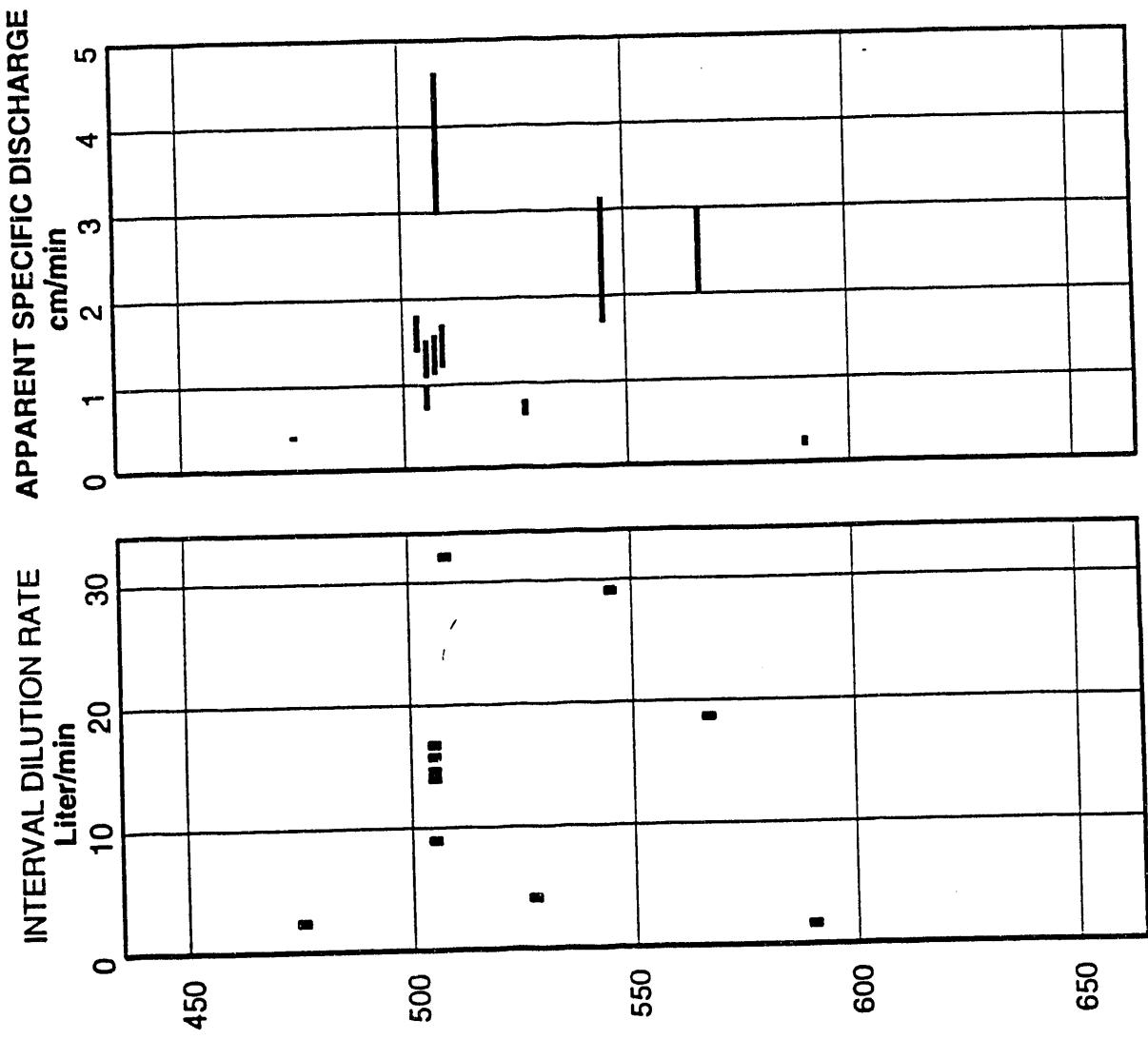


Figure 5. Calculated dilution r_{t-s} and specific discharge in all intervals

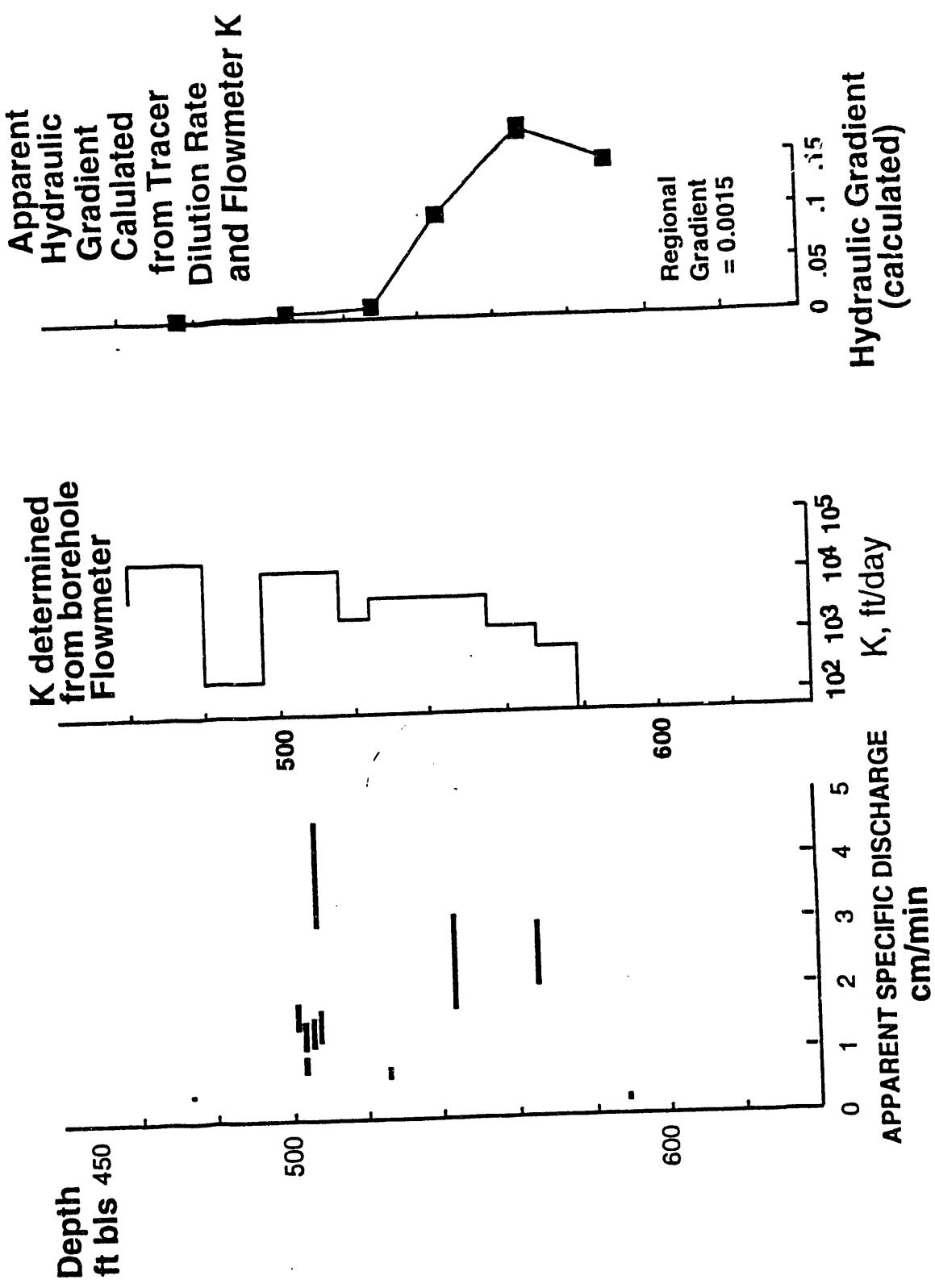


Figure 6. Apparent hydraulic gradient responsible for observed tracer dilution rate in test intervals, as calculated from hydraulic conductivity profile of Morin et al (1992) and tracer dilution rates

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