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ENVIRONMENTAL RESEARCH BRIEF

Macrodispersion and Spatial Variability of Hydraulic Conductivity in a Sand and Gravel Aquifer, Cape Cod, Massachusetts

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Introduction

Macrodispersion is the field-scale hydrodynamic spreading of solutes in an aquifer caused by local variations in ground-water velocity. These variations are caused, in large part, by small-scale variations in the hydraulic properties within the aquifer. Several stochastic transport equations have been developed that relate macrodispersion to aquifer heterogeneity, particularly spatial variations of hydraulic conductivity (K) (Dagan, 1982; Gelhar and Axness, 1983; Neuman et al., 1987). These equations have been field-tested to a limited degree by comparing the macrodispersion observed in field tracer tests to that predicted using a statistical analysis of the variability in K. The tracer test conducted in a sandy aquifer at Base Borden, Ontario (Sudicky, 1986; Freyberg, 1986) was a pioneering effort in such studies.

The link between macrodispersion and aquifer heterogeneity has been further investigated in experiments conducted by the U.S. Geological Survey (USGS) on Cape Cod, Massachusetts. As part of the USGS studies, a natural-gradient tracer test was conducted in which the transport of bromide, a nonreactive tracer, was monitored in the sand and gravel aquifer for two years (LeBlanc et al., in press). From analyses of spatial moments of the distribution of bromide at 16 times during the test, a dispersivity tensor was calculated for the field transport experiment (Garabedian et al., in press). As a complementary effort, detailed investigations of the variability of K in the aquifer were made at the tracer-test site, and the stochastic transport equations developed by Gelhar and Axness (1983) were used in conjunction with the statistical analysis of the K data to estimate macrodispersion for the aquifer. This Research Brief summarizes these investigations of the variability in K at the Cape Cod site and the relation of that variability to macrodispersion. This research was supported by the USGS Toxic-Substances Hydrology Program and the R. S. Kerr Environmental Research Laboratory of the U.S. Environmental Protection Agency.

Two methods of measuring K were evaluated: permeameter analyses of cores and flowmeter tests in wells. More than 1900 estimates of K were obtained from the permeameter and flowmeter tests. Geostatistical analyses of these data yielded estimates of the mean, variance, and correlations scales for the K distribution in the aquifer.

Estimates of macrodispersivities based on the statistical analysis of the K distribution agreed well with the macrodispersivities calculated from the tracer test. The range in asymptotic longitudinal dispersivities that was estimated from the statistical properties of the flowmeter K data, using the equations of Gelhar and Axness (1983) and assuming horizontal isotropy, was 0.23 to 1.2 meters; this range brackets the value of 0.96 meters calculated from the tracer test. The theory also correctly predicted the tracer-test result that longitudinal dispersion greatly exceeds transverse dispersion. The components of transverse dispersivity were underestimated by the transport theory, however, probably because temporal variations in the direction of flow caused additional dispersion of the tracer during the field experiment that was not accounted for in the theory of Gelhar and Axness (1983). Estimation of the transverse horizontal dispersivity was greatly improved after the effects of transient flow were incorporated using Rehfeldt's (1988) modification of the transport theory.

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Objectives

The objectives of this research were to:

1. Evaluate methods for determining the small-scale variability of K for a sand and gravel aquifer.
2. Statistically characterize the spatial distribution of K at the Cape Cod tracer-test site.
3. Assess the applicability of the stochastic transport equations for estimating macrodispersion from the variance and correlation scales of the spatial distribution of K.

Methods of Measuring Hydraulic Conductivity

Two methods were used to determine K over small intervals of the aquifer: laboratory multi-port-permeameter tests of intact cores (Wolf, 1988; Wolf et al., in press) and in-situ borehole flowmeter tests (Hess, 1989). For the permeameter measurements, relatively undisturbed, 4.8-cm (centimeter) - diameter cores of the medium to coarse sand and gravel aquifer were obtained using the method of Zapico et al. (1987). Cores were taken at 16 locations (Figure 1) from a zone that was 6 to 7.5 meters thick and located immediately below the water table. Lateral distances between coring locations ranged from 1 to 24 meters. X-rays were taken of the cores and the resulting radiographs were used to identify intervals within the cores that had similar stratigraphy or inferred grain size. These were the intervals over which permeameter measurements were made.

A schematic of the constant-head, multi-port permeameter is shown in Figure 2. The liner in which the core was collected served as the permeameter body, and manometer probes were inserted through the liner into the core at the chosen intervals. K was calculated from permeameter tests on 825 vertical core intervals which averaged 7.3 cm in length. The K values of intervals which contained large gravel were not included in the final data set because the large gravels obstruct flow in the permeameter, and the resulting K values were thought to be non-representative of the aquifer (Wolf et al., in press).

Borehole flowmeter tests were conducted in sixteen 5-cm diameter wells screened over a 12-m interval just below the water table. The wells were installed near the coring locations and were separated by distances of 1 to 24 meters (Figure 1). The borehole flowmeter test is based on a method developed by Hufschmied (1986) and modified by Rehfeldt et al. (1989). This procedure involves measuring the incremental increase in discharge up the well with a highly sensitive, impeller flowmeter, while maintaining a constant drawdown in the well by pumping near the water table at a steady rate (Figure 3). The method is analogous to a standard aquifer test, except that discharge is measured at short intervals along the screen, instead of only at the well head. This method allows calculation of K for each interval.

About 70 estimates of K over vertical intervals of 15 cm were obtained in each of the 16 wells using the flowmeter method, for a total of 1109 measurements. Only the 668 K values from the zone above an altitude of 6 meters were used in the final analysis of the spatial distribution of K. This is the vertical interval over which permeameter measurements were made and through which the bromide tracer traveled in the natural-gradient test. The array of wells and coring locations is offset about 25 meters from the tracer-test site (Figure 1). The statistical characterization of the K distribution at this location should be representative of the tracer-test zone as well because the depositional environment of the fluvially-derived glacial-outwash sediments is consistent across the test area.

Results of Flowmeter and Permeameter Tests

Both methods produced detailed profiles of the variability of K with altitude within the aquifer. Figure 4 presents four profiles obtained by each method from the central cluster (Figure 1) where wells and coring locations are separated by only one meter from their nearest neighbor. A high degree of variability is observed in the vertical direction for both types of K measurements. Greater spatial continuity is observed in the horizontal direction; several zones of similar K are evident in Figure 4. Some of these zones are horizontally continuous across the entire area of investigation. From these qualitative observations, the horizontal correlation scale of the K distribution was expected to be much greater than the vertical correlation scale.

The borehole-flowmeter method yielded a geometric mean K of 0.11 cm/s (centimeters per second) (Table 1), which is similar to the horizontal mean of 0.13 cm/s estimated from a nearby aquifer test (LeBlanc et al., 1988) and from the tracer test (LeBlanc et al., in press). In contrast, the geometric mean of the permeameter K values was 0.035 cm/s. This value represents a vertical mean because the permeameter tests were conducted on vertical cores. The ratio of the flowmeter to permeameter means (3:1) is similar to the horizontal-to-vertical anisotropy (2:1 to 5:1) previously reported for this aquifer (LeBlanc et al., 1988), which suggests that measurement direction may cause the difference in means obtained from the two methods. However, if K within the thin, uniform intervals over which permeameter measurements were made (5 to 10 cm) is isotropic, then the permeameter tests should have yielded reasonable estimates of horizontal K. A comparison of measurements on intact and homogenized, repacked cores (Wolf, 1988) seems to support the assumption of isotropy at the scale of the permeameter measurements. Wolf et al. (in press) address other possible causes of the underestimation of K by the permeameter method, including non-representative sampling and loss of porosity in the samples by compaction.

The variances of the natural logarithm of K (lnK) for the two measurement techniques also differed (Table 1). The flowmeter variance of 0.24 was significantly higher than the permeameter variance of 0.14, even though the averaging interval of 7.3 cm for the permeameter measurements was half of the 15-cm averaging interval for the flowmeter measurements.

The permeameter tests were more laborious and time consuming than the flowmeter tests. A flowmeter profile could be obtained in half a day in the field, whereas an equivalent permeameter profile required a half-day of field sampling and several days of laboratory analyses. The flowmeter method was a more efficient method for obtaining detailed profiles of K and yielded a mean value similar to those estimated by other field tests conducted in this aquifer. The flowmeter method has also been used successfully in other aquifers (Hufschmied, 1986; Rehfeldt et al., 1989; Molz et al., 1989). In the flowmeter-test analysis, however, induced flow into the well and aquifer stratification are both assumed to be horizontal. Significant deviation from these assumptions in some situations could limit the usefulness of the flowmeter test for determining the vertical distribution of horizontal K.

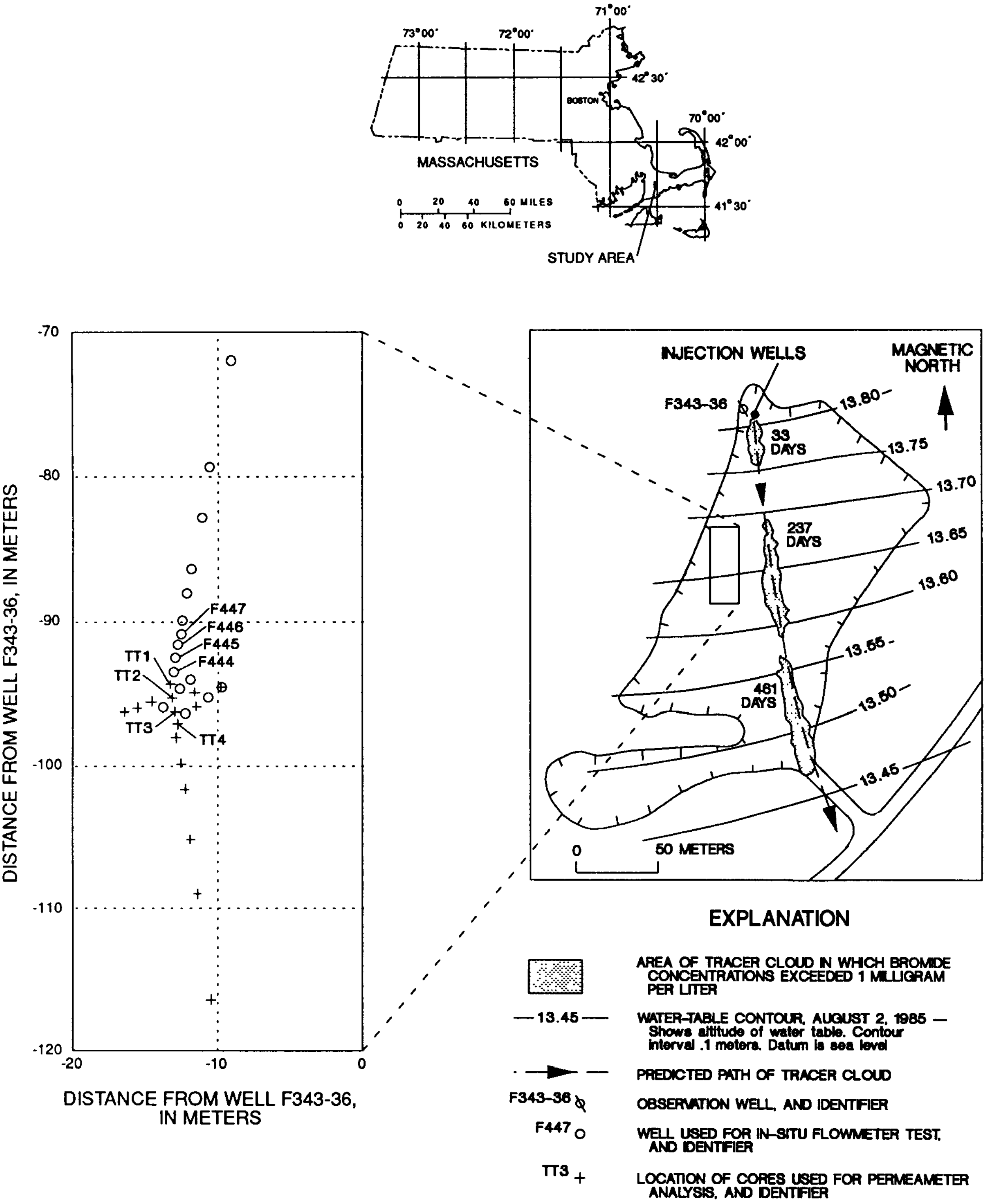

Figure 1. Tracer-test site in abandoned gravel pit, showing water-table contours, observed location of nonreactive bromide tracer cloud at various times after injection, location of long-screened wells used for borehole-flowmeter tests, and location of coring sites used for multi-port-permeameter tests. Water-table map and bromide-cloud areas (from LeBlanc et al., in press).

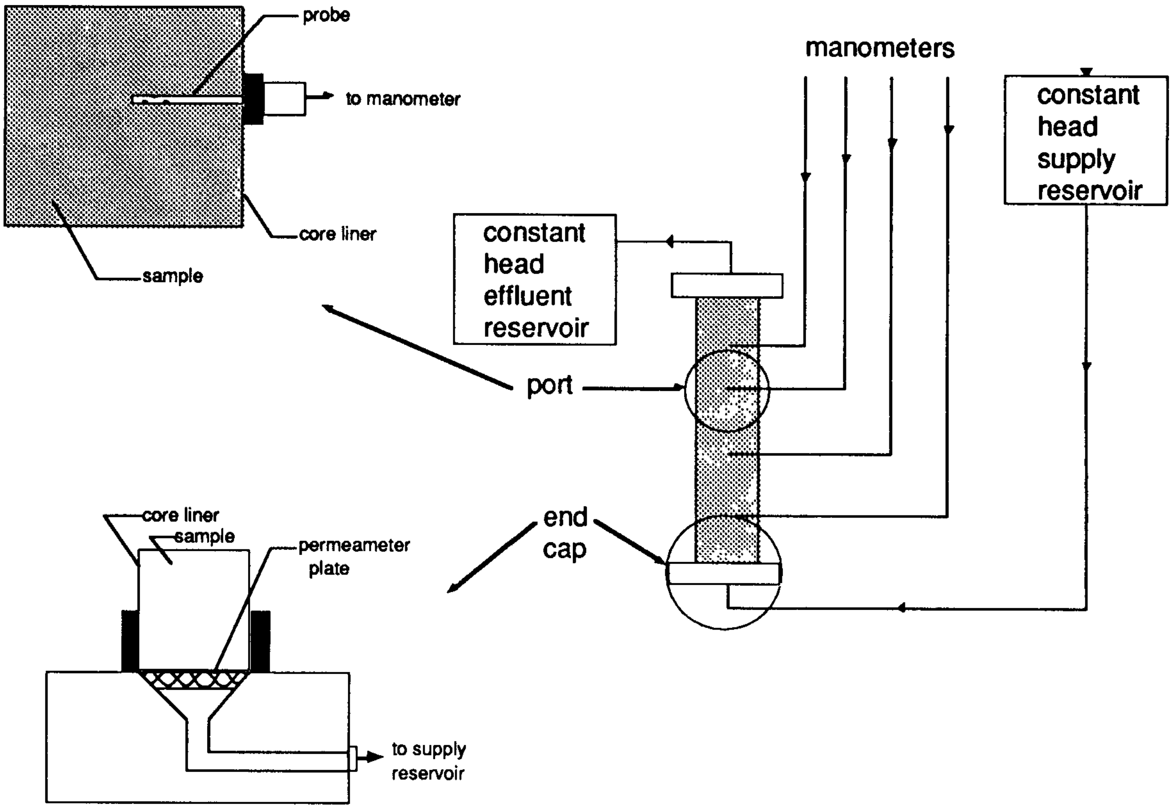

Figure 2. Schematic of multi-port, constant-head permeameter used to measure hydraulic conductivity on 5-cm-diameter cores (from Wolf et al., in press).

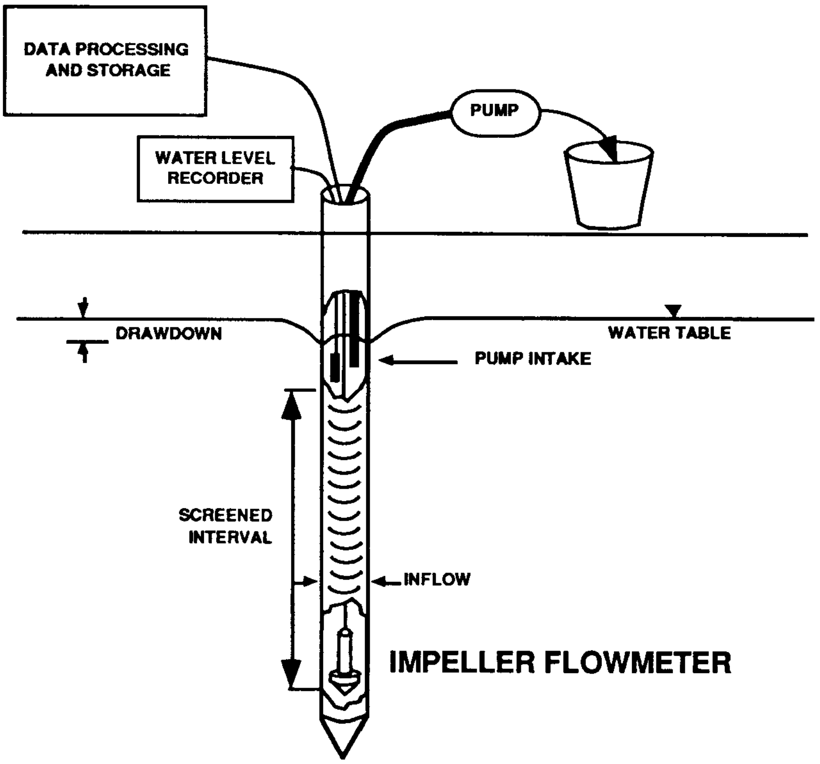

Figure 3. Schematic of hydraulic test used to measure hydraulic conductivity in 5-cm-diameter, long-screened wells using an impeller flowmeter.

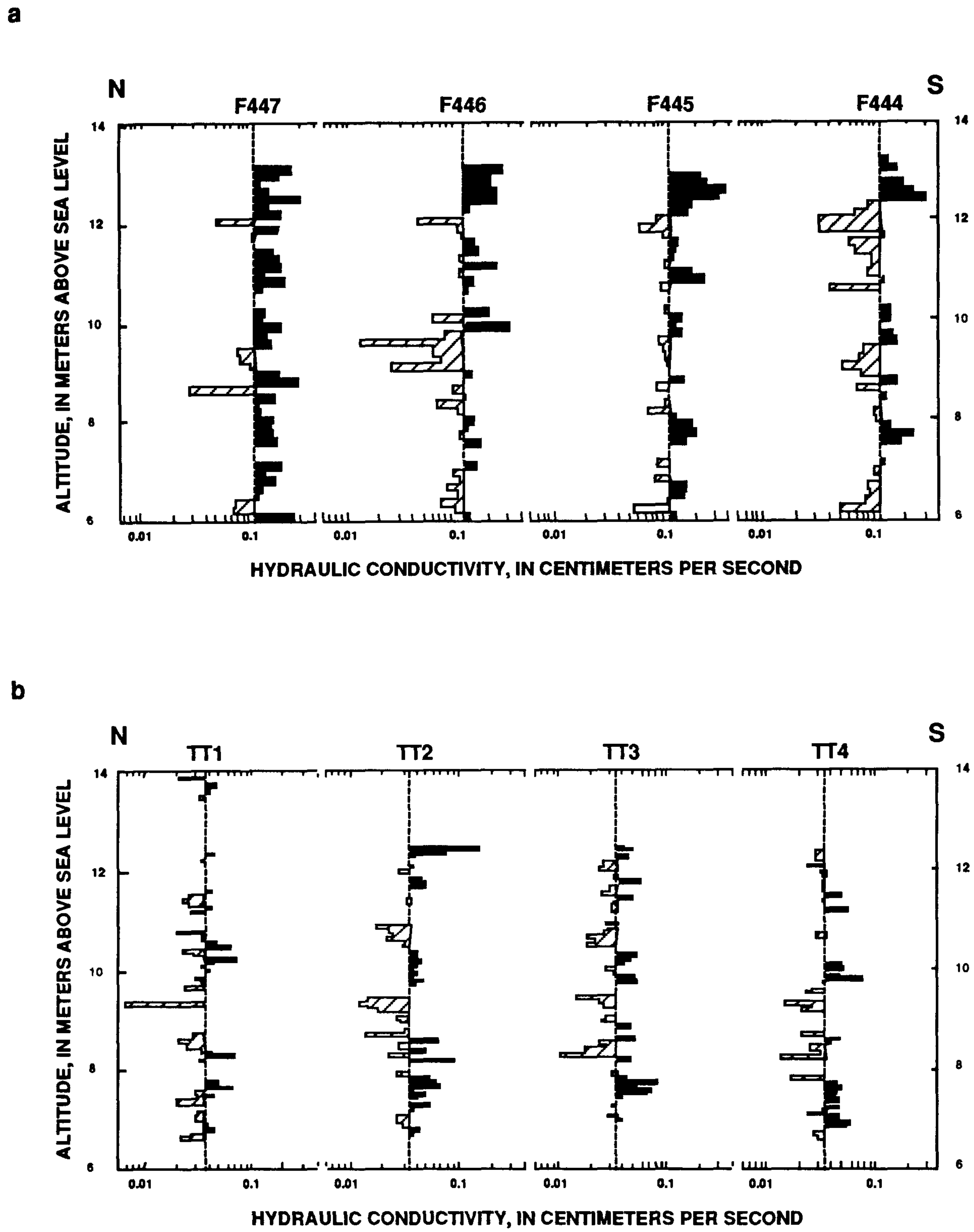

Figure 4. Hydraulic-conductivity profiles from (a) borehole-flowmeter tests and (b) permeameter tests for the central cluster where sampling locations are separated by approximately one meter. Dotted lines indicate the respective geometric mean hydraulic-conductivity values. Cross-hatched shading indicates zones of hydraulic conductivity greater than the geometric mean. Slanted-line shading indicates zones less than the geometric mean.

Table 1. Results of geostatistical analysis of hydraulic-conductivity (K) data from permeameter and borehole-flowmeter tests.

	Flowmeter	Permeameter
Number of K values	668	825
Mean vertical spacing (centimeters)	15	7.3
Geometric mean (centimeters per second)	.11	.035
Variance of natural logarithm of K	.24	.14
Vertical correlation scale (meters)		
Minimum	.08	.13
Best-fit	.19	.18
Maximum	.46	.39
Horizontal correlation scale (meters)		
Minimum	1.4	.9
Best-fit	2.6	1.2
Maximum	5.2	2.6

Geostatistical Analysis

A geostatistical analysis of the spatial variability of K was performed on the borehole-flowmeter and permeameter data to obtain estimates of the correlation structure. A variogram (Journel and Huijbregts, 1978) in the vertical direction for the permeameter data is shown in Figure 5. A negative-exponential model fit this experimental variogram well (Figure 5) and was applied to all other variograms during the analysis. Estimates of the correlation scales were obtained by fitting this model to the variogram values using a sill value that was similar to the sample variance. Models were initially fit by minimizing the sum of squares of the difference between the model and variogram values. A visual check was also conducted and, in some cases, the correlation scale and sill value were adjusted slightly to provide a better fit of the rising limb of the model to the variogram values.

The estimated vertical correlation scales were similar for the two data sets (Table 1). Best-fit vertical correlation scales were 0.19 and 0.18 meters for the flowmeter and permeameter data, respectively. By incorporating uncertainty associated with the sample variance using a method developed by Rehfeldt (1988), a range of estimates around the best-fit value was found to be 0.08 to 0.46 meters for the flowmeter measurements and 0.13 to 0.39 meters for the permeameter measurements.

The horizontal variogram values (Figure 6) showed more deviation about the fitted model than did the vertical variogram values (Figure 5). This may be due, in part, to the limited number of sampling locations in the horizontal direction; only 16 locations, spaced 1 to 24 meters apart, were used for each type of hydraulic-conductivity test. The horizontal correlation scales ranged from 1.4 to 5.2 and 0.9 to 2.6 meters, with best-fit values of 2.6 and 1.2 meters, for the flowmeter and permeameter data, respectively (Table 1). Because of the large range in values, the differences between the permeameter and flowmeter horizontal correlation scales are probably not statistically significant. In addition, no statistically significant horizontal anisotropy was observed during the analysis. Collection of data from additional sampling locations may be necessary to detect any horizontal anisotropy in the K distribution. If horizontal anisotropy is present, it is probably small. The large ratio of horizontal to vertical correlation scales (5:1 to 25:1) obtained for both data sets is consistent with the predominant horizontal layering observed in the stratigraphy at the site.

Macrodispersion Estimates

Dispersivity values were estimated using the stochastic transport theory of Gelhar and Axness (1983) and the variance and correlation scales determined in the geostatistical analysis (Table 2). Isotropy in the plane of stratification was assumed in the analysis (Case 1, Gelhar and Axness, 1983) because there was no evidence of horizontal anisotropy. The range in asymptotic longitudinal dispersivity estimated from the flowmeter data was 0.23 to 1.2 meters, with a best-fit value of 0.5 meters; this range encompasses the value of 0.96 meters observed in the tracer test (Garabedian et al., in press). The dispersivities calculated from the permeameter data were consistently lower than those from the flowmeter data (Table 2) because the estimates of variance and horizontal correlation scale from the permeameter data are lower, in general, than those from the flowmeter measurements.

Application of the stochastic equations to the results of the geostatistical analysis also indicated that longitudinal dispersivity exceeds the transverse components, as was observed in the tracer test. The stochastic analysis, however, underestimated the magnitude of the transverse components (Table 2). Shifts in the hydraulic-gradient direction during the two-year-long tracer test (Garabedian et al., in press) may have caused additional lateral mixing and, thus, enhanced the transverse horizontal dispersion observed in the tracer test. An estimate of 0.025 meters for transverse horizontal dispersivity (Table 2) was calculated using the method of Rehfeldt (1988) that incorporates the effects of the transient flow on dispersion. This estimated value agrees well with the transverse horizontal dispersivity of 0.018 meters observed in the tracer test (Garabedian et al, in press).

Effective Hydraulic Conductivity

The correlation scales from the variogram analyses were also used in the stochastic transport equations to estimate the anisotropy in the effective K tensor. The horizontal-to-vertical anisotropy ratio of K, estimated by the method of Gelhar and Axness (1983) using either the flowmeter or permeameter correlation scales, is about 1.2:1, which is slightly smaller than the anisotropy of 2:1 to 5:1 obtained from the nearby aquifer test (LeBlanc et al., 1988). The anisotropy of the effective K tensor is also smaller than the ratio of mean K values obtained from the flowmeter and permeameter measurements (3:1). This suggests that the difference between the horizontal-K values from the flowmeter and the vertical-K values from the permeameter may be only partly explained by anisotropy and different measurement directions.

Conclusions

The following conclusions can be made on the basis of results of this research:

1. Flowmeter tests in long-screened wells provided a relatively fast and easy method for assessing the small-scale variability in K (hydraulic conductivity) at the Cape Cod site. The resulting geometric

Table 2. Components of macrodispersivity estimated from hydraulic-conductivity data using the stochastic theory of Gelhar and Axness (1983) and the modifications of the theory of Rehfeldt (1988).

	Variance of lnK	Correlation Scales (meters)		Macrodispersivity (meters)		
		Horizontal	Vertical	Longitudinal	Transverse Horizontal	Transverse Vertical
Flowmeter						
Minimum	0.20	1.4	0.08	0.23	10^{-8}	10^{-8}
Best-fit	.24	2.6	.19	.50	10^{-7}	10^{-7}
Maximum	.29	5.2	.46	1.2	10^{-7}	10^{-7}
Permeameter						
Minimum	.12	.9	.13	.09	10^{-7}	10^{-7}
Best-fit	.13	1.2	.18	.12	10^{-7}	10^{-6}
Maximum	.16	2.6	.39	.33	10^{-6}	10^{-6}
Tracer Test Garabedian et al. (in press)				.96	.018	.0015
Flowmeter, accounting for transient flow				.96	.025	—

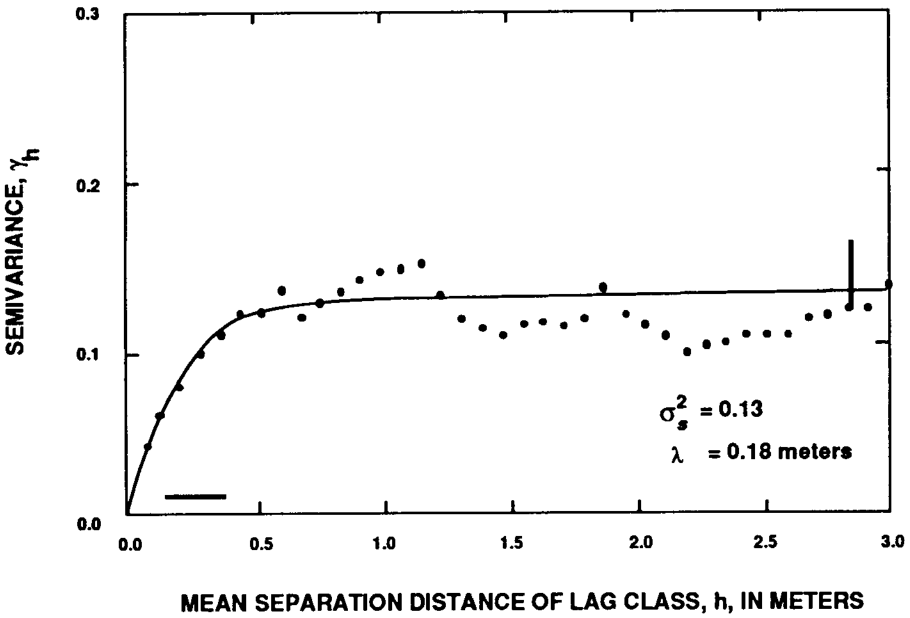

Figure 5. Vertical variogram of natural-logarithm of hydraulic conductivity from the permeameter data. Exponential model of the form $\gamma_h = \sigma_s^2(1-\exp(-h/\lambda))$ was fit to the experimental variogram, where γ_h = the semivariance, σ_s^2 = the sill value, and λ = the correlation scale. Vertical bar indicates 95% confidence interval about the sample variance. Horizontal bar indicates the corresponding vertical correlation-scale range.

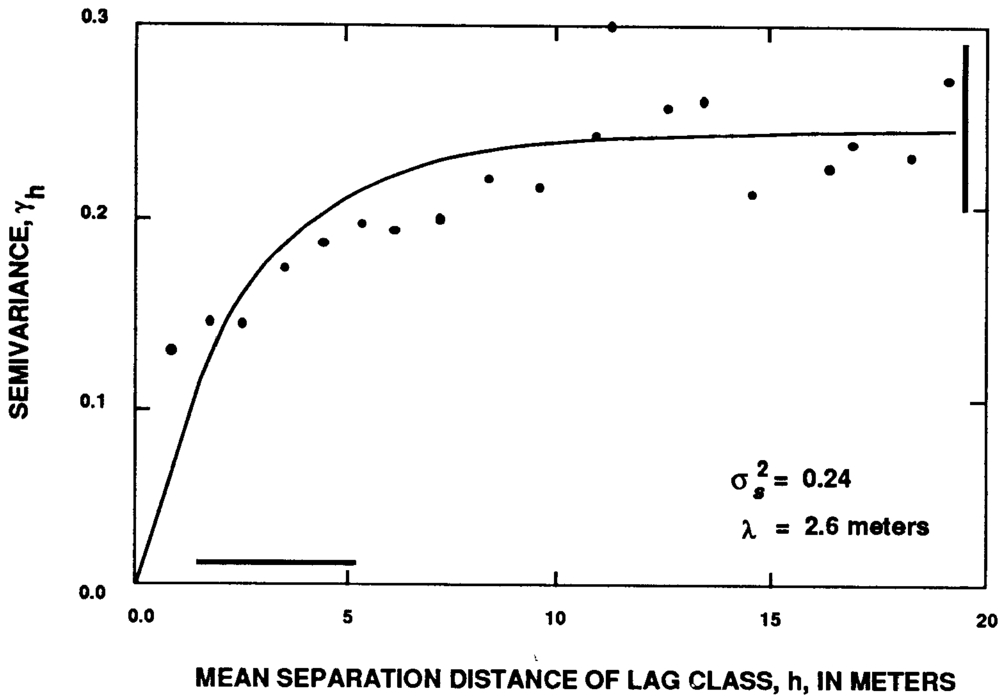

Figure 6. Horizontal variogram of natural-logarithm of hydraulic conductivity from the borehole-flowmeter data. Exponential model of the form $\gamma_h = \sigma_s^2 (1 - \exp(-h/\lambda))$ was fit to the experimental variogram, where γ_h = the semivariance, σ_s^2 = the sill value, and λ = the correlation scale. Vertical bar indicates 95% confidence interval about the sample variance. Horizontal bar indicates the corresponding horizontal correlation-scale range.

mean of K was similar to the mean calculated from tracer and aquifer tests.

2. The permeameter method of measuring K was more time consuming and produced a mean which was significantly less than that determined by other methods. This lower mean may be the result of non-representative sampling, loss of porosity in the samples, and anisotropy in the sediments.

3. The permeameter results provided an estimate of the vertical correlation scale which is similar to that from the flowmeter tests. However, estimates of the variance of lnK and the horizontal correlation scale from the permeameter tests are lower, in general, than those from the flowmeter measurements.

4. Horizontal anisotropy in the K field was not observed, and isotropy in the plane of stratification was assumed in the macrodispersion calculations. A large ratio of horizontal to vertical correlation scales was observed and ranged from 5:1 to 25:1.

5. The ratio of horizontal to vertical K indicated by the stochastic analysis (1.2:1) was less than the range in ratios calculated from a nearby aquifer test (2:1 to 5:1).

6. Stochastic transport equations predicted a range of asymptotic longitudinal-macrodispersivities from the flowmeter measures of K variability (0.23 to 1.2 meters) which brackets the value observed in the tracer test (0.96 meters). Estimates of longitudinal macrodispersivity using statistical parameters from the permeameter measurements were consistently lower than the tracer-test value.

7. Transverse horizontal and transverse vertical dispersivities were underestimated, probably because transient flow effects are not taken into account in the stochastic transport equations of Gelhar and Axness (1983).

8. The transverse horizontal dispersivity (0.025 meters) estimated by the modified stochastic equations of Rehfeldt (1988), which incorporate the effects of lateral shifts in the hydraulic-gradient direction, agrees well with the value observed in the tracer test (0.018 meters).

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