FIELD STUDY OF MACRODISPERSION IN A HETEROGENEOUS AQUIFER

2. OBSERVATIONS OF HYDRAULIC CONDUCTIVITY VARIABILITY

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ABSTRACT

Observations of the spatial variability of the hydraulic conductivity field at the site of a large-scale natural-gradient tracer experiment located at Columbus Air Force Base in Mississippi are presented. Direct measurements of hydraulic conductivity of the heterogeneous alluvial aquifer at the site were made using a variety of methods including aquifer tests, borehole flowmeter logging, double-packer tests, slug tests, and a newly developed laboratory permeameter to test undisturbed soil cores. Several methods of indirectly estimating the variability of hydraulic conductivity were also evaluated, including soil grain-size analyses, surface geophysical surveys, and mapping of sedimentary facies. The borehole flowmeter method was shown to be the most practical and effective method for measuring conductivity variability. The spatial covariance of the hydraulic conductivity field was examined using 2187 flowmeter measurements obtained from 49 fully-penetrating test wells. Estimates of the log hydraulic conductivity variance ($\sigma_{lnK}^2$) and the horizontal and vertical correlation scales ($\lambda_h$ and $\lambda_v$) of 4.5, 12 m, and 1.5 m, respectively, were calculated assuming second-order stationarity of the conductivity field. Large-scale spatial variations in the mean groundwater velocity indicated by the natural-gradient tracer experiment, which were shown to be a direct result of contrasts in the mean hydraulic conductivity along the plume pathway, strongly suggested the presence of a conductivity trend. The measured hydraulic conductivity data were subsequently detrended using least-squares regression to remove three-dimensional polynomials. The third-order polynomial was judged the best representation of the conductivity drift based on its overall compatibility with the groundwater flow field inferred from the tracer plume observations. Significantly lower estimates for $\sigma_{lnK}^2$, $\lambda_h$, and $\lambda_v$ of 2.8, 5.3 m, and 0.7 m, respectively, were obtained from the third-order log conductivity residuals. The experience with the borehole flowmeter technique shows the feasibility of observing the statistical parameters of the hydraulic conductivity variability required for stochastic models of macrodispersion. The availability of this technique for acquiring extensive hydraulic conductivity measurements in three dimensions also suggests the possibility of applying more deterministic advection-based transport models in the future.
INTRODUCTION

The first paper of this series [Boggs et al., these proceedings] describes the overall objectives, methods, and qualitative results of a natural-gradient tracer experiment conducted at a site near Columbus, Mississippi. The study represents one component of a research effort sponsored by the Electric Power Research Institute to improve methods for predicting the transport and fate of contaminants in groundwater. In conjunction with the field tracer test, a detailed characterization of the alluvial aquifer at the Columbus site was conducted. These investigations centered on a detailed description of the spatial distribution of hydraulic conductivity at the tracer test site. Data obtained from the natural-gradient experiment and the aquifer investigations were intended to provide the basis for validation of groundwater solute transport models.

A secondary goal of the Columbus study was to develop a practical methodology for measuring hydraulic conductivity variability. It is generally recognized that the degree of heterogeneity of the hydraulic conductivity field associated with an aquifer largely controls the movement and dispersion of groundwater solutes. Therefore, a means of quantifying spatial variability at reasonable expense is essential to the application of current transport models to practical problems. For example, the stochastic theories of Gelhar and Axness [1983] and Dagan [1984] treat the hydraulic conductivity as a random process, and solve stochastic forms of the transport equations. The dispersivity terms associated with these models are functions of the covariance of the log hydraulic conductivity field, and application of these models requires a large number of hydraulic conductivity measurements in three dimensions for estimation of the log conductivity covariance. Likewise, if modeling is approached deterministically the relationship between hydraulic conductivity variability and dispersive transport indicates that large numbers of hydraulic conductivity measurements over the modelled region will be needed for meaningful predictions. As part of the site characterization program, several methods of measuring hydraulic conductivity variability were evaluated to identify a method of obtaining the extensive conductivity data for practical modeling applications.

In this paper we present observations of the spatial variability of hydraulic conductivity for the alluvial aquifer at the Columbus research site. The methods of measuring or indirectly estimating the spatial distribution of hydraulic conductivity are briefly described and comparatively evaluated. Procedures used in estimation of the hydraulic conductivity covariance are presented along with interim results of the covariance analysis for each field or laboratory technique tested. The paper emphasizes the borehole flowmeter description and results because this technique provided the most comprehensive description of the spatial variability of hydraulic conductivity of all methods evaluated.
METHODS OF ESTIMATING HYDRAULIC CONDUCTIVITY VARIABILITY

Both direct and indirect methods were evaluated for estimating the spatial variability of hydraulic conductivity at the test site. The direct techniques included borehole flowmeter measurements, packer tests, slug tests, and laboratory permeameter tests on minimally-disturbed core samples. Attempts were made to indirectly estimate hydraulic conductivity variability from soil grain-size analyses and from surface geophysical surveys using direct current resistivity and streaming potential data.

Borehole Flowmeter Method

The borehole flowmeter method is similar to the conventional aquifer test except that measurements of flow entering the well at different elevations are made as the well is pumped at a constant rate (Figure 1a). The hydraulic conductivity of each interval or layer of the aquifer is proportional to the measured flow for that interval. The layer hydraulic conductivities are computed using a linearized form of the Cooper-Jacob well equation. The key assumptions of the method are (1) the aquifer is layered and each layer is homogeneous and of uniform thickness, (2) the storage coefficient of each layer is linearly related to the layer transmissivity, and (3) the well losses attributable to each layer can be estimated. Further information regarding the theoretical basis for the method and field procedures for its implementation can be found in Rehfeldt et al. [1989a] and Hufschmied [1983].

Measurements were made with an impeller flowmeter as shown in Figure 1b. The device basically consists of a lightweight plastic impeller suspended between two needle bearings. Rotation of the impeller produced by flow through the meter is detected by optical sensors. The optical signal is converted to a voltage that is proportional to the rate of rotation. Laboratory calibration of the instrument is required before and after field testing to convert recorded voltage measurements to flowrates. In a 5.1-cm diameter well, the lower threshold of flow measurement for the impeller meter is approximately 0.005 L/s. The sensitivity of the flowmeter varies as a function of the discharge, but is also on the order of 0.005 L/s. This corresponds to a detection limit for hydraulic conductivity measurement of about 10^-4 cm/s [Rehfeldt et al., 1989a].

A map showing the locations of 58 wells tested by the flowmeter method is presented in Figure 2. All wells were constructed of 5.1-cm diameter flush-joint PVC slotted pipe, and were screened over the full saturated thickness of the aquifer. In designing the flowmeter test well network, the following requirements were considered. First, sufficient closely-spaced wells were needed for variogram analysis to adequately define the horizontal correlation scale. For this purpose three well clusters (K22-K28, K29-K35, and K51-K55) were installed. Second, proper estimation of the variance of lnK required that some of the wells be spaced sufficiently far apart so as to be uncorrelated. Likewise, delineation of trends in the conductivity field required coverage of essentially the entire experimental site using widely-spaced wells. Third, to estimate horizontal anisotropy in the lnK field required linear
Figure 1(a). Schematic Diagrams of Flow to Well in a Layered Aquifer, Cumulative Flow Profile, and Estimated Hydraulic Conductivity Profile

Figure 1(b). Impeller-Type Borehole Flowmeter
Figure 2. Borehole Flowmeter Test Well Locations
arrays of test wells along at least three directions. Wells located along	hree lines in the near-field region of the tracer test site were designed
to satisfy this requirement. Flowmeter measurements within each well were
made at 15-cm vertical intervals. To date, a total of 2483 estimates of
hydraulic conductivity have been obtained at the tracer test site from
flowmeter measurements.

Other Direct Methods

Piezometer slug tests and laboratory permeameter tests on
minimally-disturbed soil cores were also evaluated as methods for directly
measuring hydraulic conductivity variations. Slug tests were conducted in
22 partially-penetrating piezometers. All piezometers used in these tests
were 5.1 cm in diameter, and were constructed with a 60-cm slotted screen
on the lower end. Tests were performed by introducing water into the
piezometer to instantaneously increase the water level. Decay of the
hydraulic head was monitored with a pressure transducer and data logging
system. In addition, detailed hydraulic conductivity measurements were
made on ten soil cores obtained from a single corehole using a specially
designed laboratory permeameter. Cores were 8 cm in diameter and 76 cm in
length. Conductivity measurements were made over 7.6-cm segments of each
core, yielding a total of 88 measurements for the corehole [Boggs et al.,
1990].

Indirect Methods

Several methods of indirectly estimating the variability of hydraulic
conductivity or some related physical property of the aquifer were
evaluated. An empirical method developed by Seiler [1973] relating
hydraulic conductivity to grain size was used to estimate conductivity
values for 214 soil samples. Soil samples were obtained from 30 separate
coreholes using a 5.1-cm diameter by 46-cm long split-barrel sampler.
Samples were collected at vertical intervals of 0.75 to 1.5 m during
drilling.

An attempt was made to estimate the horizontal correlation scale from
direct current resistivity (DCR) and streaming potential (SP) surface
geophysical survey data obtained during early site reconnaissance
investigations. DCR horizontal profiling was performed at 30.5-m
intervals along four parallel transects spaced 61 m apart encompassing the
experimental site. Wenner electrode spacings of 1.5, 3.0 and 6.1 m were
used. The SP survey was conducted over the same region using a horizontal
measurement interval of 15.2 m. Rehfeldt et al. [1989b] obtained indirect
estimates of the horizontal and vertical correlation scales by mapping
soil facies in a gravel quarry located approximately 1.5 km east of the
Columbus site. An exposure of the alluvial deposits approximately 20 m in
length by 2 m in height was mapped. To estimate the correlation scales,
hydraulic conductivities were assigned to the different facies
identified. The resulting conductivity field was sampled over a fine grid
and a variogram constructed from these data.
GENERAL FEATURES OF THE HYDRAULIC CONDUCTIVITY FIELD

The borehole flowmeter measurements provided the most complete description of the spatial distribution of hydraulic conductivity at the test site of all methods evaluated. It is useful to qualitatively examine the general features of the hydraulic conductivity field indicated from the flowmeter measurements before proceeding to the covariance analysis. A north-south trending vertical profile of hydraulic conductivity that approximately follows a groundwater streamline passing through the tracer injection site is shown on Figure 3. Note that the base of the conductivity profile represents the approximate top of the Eutaw aquitard, whereas the top of the profile represents the uppermost flowmeter measurements. The uppermost measurement for any particular test well was dependent on the drawdown in the well during pumping and on the elevation of the phreatic surface at the time of testing. This accounts for the variable elevation of the top of the profile.

![Figure 3. Hydraulic Conductivity Profile Derived From Borehole Flowmeter Measurements](image)

The hydraulic conductivity profile illustrates the extreme variability of the aquifer with conductivities typically ranging over two to four orders of magnitude at each test well site. The profile also indicates that the highest conductivity zones are found below approximately elevation 58 m at wells (e.g., K7) located upgradient (south) of the injection site, whereas 20 to 30 m downgradient of the injection point the most permeable zones are generally found above this elevation. It is evident from both the
profile and the map of depth-averaged conductivity (Figure 4) that the injection site is located in a region of relatively low mean conductivity (i.e., on the order of $10^{-3}$ cm/s), while the mean conductivity in the far-field region of the test site is from one to two orders of magnitude larger. This trend had a pronounced effect on the evolution and ultimate configuration of the bromide tracer plume during the natural-gradient experiment [Boggs et al., these proceedings].

![Figure 4. Depth-Averaged Hydraulic Conductivity Derived From Borehole Flowmeter Measurements](image)

**HYDRAULIC CONDUCTIVITY COVARIANCE ESTIMATION**

**Method**

The spatial variability of hydraulic conductivity was statistically characterized through a covariance analysis of the sample measurements. In general, the log transforms of the hydraulic conductivity measurements were used to estimate a sample variogram. The variance of the natural
logarithm of hydraulic conductivity (lnK) was computed directly from the sample measurements. The correlation scales of log conductivity were then determined by fitting the stationary negative-exponential variogram given in Equation (1) to the sample variogram. The method of least-squares was used to fit the rising limb of the exponential variogram to the sample variogram while holding the sill value equal to the sample variance.

\[ y(h) = \sigma^2 [1-\exp(-h/\lambda)] \]  

where \( y(h) \) = stationary negative-exponential variogram  
\( h \) = lag or separation distance between measurement couples  
\( \sigma^2 \) = sill (assumed equal to sample variance)  
\( \lambda \) = correlation scale

Two separate variogram analyses were performed for the borehole flowmeter measurements. In the first case, variograms were estimated directly from the lnK measurements assuming second-order stationarity of the conductivity field. The second case involved a nonstationary analysis in which three-dimensional trends in the hydraulic conductivity field, represented by polynomial expressions of various order, were numerically removed from the lnK measurements using a weighted least-squares regression analysis. The variogram analysis was then applied to the lnK measurement residuals. Results were examined to determine which trend best represented the hydraulic conductivity field, and the effect of trend removal on the covariance parameter estimates.

The log hydraulic conductivity variance was calculated directly from the lnK measurements for the stationary analysis, and from the lnK residuals for the nonstationary case. The uncertainty associated with the variance was estimated using the methodology of Rehfeldt et al. [1989b] where the approximate 95 percent confidence interval about the true variance, \( \sigma_{\text{lnK}}^2 \) is given by Equation (2).

\[ \hat{\sigma}_{\text{lnK}}^2 - 2(\text{var}(\hat{\sigma}_{\text{lnK}}^2))^{0.5} < \sigma_{\text{lnK}}^2 < \hat{\sigma}_{\text{lnK}}^2 + 2(\text{var}(\hat{\sigma}_{\text{lnK}}^2))^{0.5} \]  

where

\[ \text{var}(\hat{\sigma}_{\text{lnK}}^2) = \frac{2(\hat{\sigma}_{\text{lnK}}^2)^2 \lambda_v \ dz \ W_t}{N \ dz \ W_u} \]  

\( \hat{\sigma}_{\text{lnK}}^2 \) = lnK sample variance  
\( N \) = total number of measurements  
\( \lambda_v \) = vertical correlation scale  
\( dz \) = vertical measurement interval  
\( W_t \) = total number of test wells  
\( W_u \) = number of wells separated by distance greater than \( \lambda_h \)
The upper and lower bounds of the confidence interval estimated for \( \sigma^2_{\ln K} \) were used, in turn, to provide bounding values for the uncertainty in the correlation scale estimates. Each bounding value of \( \sigma^2_{\ln K} \) was substituted for the sill value, and the rising limb of exponential variogram refitted to the sample variogram. The resulting refitted values of the correlation scales provide an indication of the uncertainty about \( \lambda_v \) and \( \lambda_h \), but do not represent true statistical confidence intervals [Rehfeldt et al., 1989b].

Because a goal of the study was to provide a data base for establishing a relationship between the spatial statistics of the hydraulic conductivity field and the observed plume dispersion during the natural-gradient tracer experiment, only those hydraulic conductivity estimates from the 49 test wells within the region actually traversed by the plume were used in the covariance analyses. These wells included K9 and K12 through K59, representing a total of 2187 conductivity measurements.

Covariance Analysis for Stationary Field

The vertical and horizontal variograms for the borehole flowmeter \( \ln K \) measurements are shown in Figure 5. Each figure shows the best fit of the exponential variogram to the sample variogram for the calculated and bounding variance (sill) values. An approximate confidence interval about
the true variance, \( \sigma^2_{\ln K} \), was estimated from Equations (2) and (3). Given the total number of \( \ln K \) measurements \((N)\) of 2187, the total number of test wells \((W_t)\) of 49, the number of wells separated by distances greater than \( \lambda_h \) of 29, and the vertical measurement interval of 0.15 m, the bounding values of the variance were,

\[
3.37 < \sigma^2_{\ln K} < 5.59 \tag{4}
\]

Table 1 summarizes the best estimates and bounding values for the covariance parameters for the borehole flowmeter measurements. Previous parameter estimates by Rehfeldt et al. [1989b] are given in parentheses for comparison.

TABLE 1

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Best Estimate</th>
<th>Lower Limit</th>
<th>Upper Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \sigma^2_{\ln K} )</td>
<td>4.5 (4.6)</td>
<td>3.4 (2.9)</td>
<td>5.6 (6.3)</td>
</tr>
<tr>
<td>( \lambda_h )</td>
<td>12.0 (12.7)</td>
<td>7.3 (6.9)</td>
<td>21.2 (22.5)</td>
</tr>
<tr>
<td>( \lambda_v )</td>
<td>1.5 (1.6)</td>
<td>0.9 (0.75)</td>
<td>2.2 (2.5)</td>
</tr>
</tbody>
</table>

In general, the previous and current best estimates of the covariance parameters differ only slightly, despite the fact that the number of measurements in the new data set (2187) was nearly twice that of the previous data set (1242), and that the new measurements were obtained primarily in a previously untested region. This suggests the statistical properties of hydraulic conductivity in the newly tested region are not significantly different than those in the previously tested area. The additional measurements reduced the confidence region around \( \sigma^2_{\ln K} \) by approximately 35 percent, i.e., from 3.4 to 2.2. However, this still represents a high degree of uncertainty in the variance estimate, and indicates that large uncertainty in \( \sigma^2_{\ln K} \) will be unavoidable for practical problems involving heterogeneous aquifers. The reduction in the \( \sigma^2_{\ln K} \) confidence interval produced corresponding decreases of 11 percent and 26 percent in the uncertainty about the horizontal and vertical correlation scales, respectively.

Covariance Analysis for Nonstationary Field

A nonstationary field may be considered a process composed of a stochastic component represented by relatively small-scale, high-frequency variations, and a deterministic component (trend or drift) representing relatively large-scale, low-frequency variations [Russo and Jury, 1987b]. Estimation of the covariance parameters for the case of a nonstationary field requires prior determination and removal of the trend before application of the variogram analysis.
The question of whether a trend exists in the hydraulic conductivity field at the Columbus site was investigated by Rehfeldt et al. [1989b] using 1242 borehole flowmeter measurements from wells K7 through K36 (Figure 2). They used ordinary least-squares regression to remove polynomial trends of orders 1, 2, and 3 from the measured data, and performed variogram analyses on the lnK residuals. They concluded that if a trend was present it was of order two or less, and found that the conductivity covariance parameter estimates from the detrended measurements fell within the 2σ range of parameter values for the undetrended case. They argued that the covariance parameters following detrending were statistically indistinguishable from those obtained from the original measurements.

The question of a trending hydraulic conductivity field was reexamined in light of the additional 1114 flowmeter measurements for wells K38 through K59 located primarily in the previously untested far-field region of the tracer test site. The method of weighted least-squares was used to fit polynomial functions to the base-ten logarithm of the hydraulic conductivity measurements. No constraints were applied to the fit. The weight associated with each conductivity measurement was based on the estimated measurement uncertainty. Rehfeldt et al. [1989a] showed that errors in the discharge profile measured by the flowmeter tended to be random and to have a much greater effect on the computed hydraulic conductivities for layers of low conductivity than for layers of high conductivity. Consequently, the uncertainty associated with low conductivity measurements is greater than that for high conductivity measurements. This is indicated by Figure 6 which shows the variation lnK deviation about the mean versus mean layer lnK obtained from an analysis of replicate flowmeter measurements. An approximate envelope bounding the

Figure 6. Plot of lnK Deviation Versus Mean Layer lnK Value With Envelope of Measurement Uncertainty (after Rehfeldt et al., 1989a)
uncertainty in $\ln K$ was obtained using these results, and was used as the weighting function in the least-squares analysis, i.e.,

$$W_i = K_i^{0.25}$$ (5)

where $W_i$ is the weighting function for the $i^{th}$ hydraulic conductivity measurement ($K_i$).

Three horizontal sections through the first-, second-, and third-order polynomial trend surfaces are shown in Figure 7 along with sections through the bromide tracer plume at corresponding elevations for comparison. Before examining the conductivity trends, it is worth noting the general features of the tracer plume evident from these figures from which inferences regarding the groundwater flow field can be drawn. First, the plume followed a nearly-linear, northerly trajectory during the experiment. A conductivity trend, if present, must be consistent with the general direction of flow indicated by the tracer movement. Second, the bromide tracer concentration distribution in the longitudinal direction was highly asymmetric at the end of the experiment. The more concentrated region of the plume was centered just downgradient of the injection point with the advancing side of the plume extending northward a distance of at least 260 m. Comparison of the longitudinal profiles of bromide concentration and measured hydraulic conductivity shown on Figure 8 indicate that the concentrated region of the plume corresponds to the zone of relatively low conductivity in the injection site vicinity, and that the long, dilute advancing side of the plume corresponds to the more permeable sediments in the region downgradient of the injection site. It is clear from these data and the observed migration of the plume that an increase in the mean groundwater velocity occurs north of the injection point as a result of an increase in the magnitude of hydraulic conductivity in this region, and that this trend was responsible for the rapid movement and dilution of the advancing side of the plume. This important aspect of the hydraulic conductivity field must be represented in any polynomial trend in order to be considered physically compatible with the available information.

The primary criterion for judging the most appropriate trend was to identify the lowest order polynomial trend that was physically consistent with the observed tracer plume migration. We observe in Figure 7 that the general trend of increasing hydraulic conductivity from west to east indicated for the first-order polynomial drift is inconsistent with the plume behavior. This trend fails to explain the general increase in hydraulic conductivity and, hence, groundwater velocity, in the region north of the injection point, and is therefore rejected. The second-order polynomial accounts for the general increase in conductivity north of the injection point, but, like the first-order trend, shows increasing conductivity from west to east in the far field that is not entirely consistent with the plume migration. One would expect the plume to have migrated more toward the northeast if such a trend were actually present. The third-order trend appears to be the lowest order trend that is physically compatible with the major features of the plume. An elongated
Figure 7. Comparison of Horizontal Sections Through Order 1, 2, and 3 Hydraulic Conductivity Trends and Horizontal Sections Through Bromide Plume Concentration 503 Days After Injection
region of relatively high hydraulic conductivity (i.e., $> 10^{-2}$ cm/s) is evident in the third-order trend that extends northward from a point approximately 20 to 30 m north of the injection site. This feature approximately conforms with the alignment and extent of the dilute advancing side of the plume. A relatively narrow zone of high mean conductivity of the approximate dimensions indicated for the third-order trend shown on Figure 7 is expected on the basis of the flowmeter measurements (Figure 4).

The vertical and horizontal variograms for the second- and third-order lnK residuals are shown in Figure 9, and the overall features of the variograms for both trends are similar. As expected, both variograms exhibit less scatter about the sill value than the variograms for the measured (undetrended) conductivity data (Figure 5), and therefore appear more stationary. Although the detrended vertical and horizontal variograms still show appreciable scatter about their respective sill values, this does not necessarily mean that "the true drift" has not been removed from the measured data. As observed by Russo and Jury (1987b) and Rehfeldt et al. [1989b], it is often difficult to discern a trend solely on the basis of the variogram.

A summary of the covariance parameter estimates for the detrended lnK data sets is given in Table 2. In general, parameter estimates for the second- and third-order lnK residuals were similar, differing by less than 15 percent. In all cases the detrended covariance parameters fell below the lower confidence limits estimated for the measured (undetrended) data.
indicating a significant difference between the detrended and undetrended parameter estimates.

**TABLE 2**

Summary of Detrended Covariance Parameter Estimates

<table>
<thead>
<tr>
<th>Trend Order</th>
<th>$\sigma_{\ln K}^2$</th>
<th>$\lambda_v (m)$</th>
<th>$\lambda_h (m)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>3.1</td>
<td>5.4</td>
<td>0.8</td>
</tr>
<tr>
<td>3</td>
<td>2.8</td>
<td>5.3</td>
<td>0.7</td>
</tr>
</tbody>
</table>

![Order 2 Trend Removed Variogram](image1)

![Order 3 Trend Removed Variogram](image2)

Figure 9. Vertical and Horizontal Variograms of Log Hydraulic Conductivity for Order-2 and Order-3 Detrended Borehole Flowmeter Data Sets

**Discussion**

The variance and correlation scales calculated from the third-order detrended data were significantly different than those estimated directly from the measured data. Whether the hydraulic conductivity field at the test site is best characterized by the variance and correlation scales estimated from the stationary or nonstationary covariance analysis cannot
be answered solely on the basis of examination of the variograms for the measured and detrended data sets. Several investigators [Russo and Jury, 1987a and 1987b, and Rehfeldt et al., 1989b] have shown that, in many cases it is impossible to identify with certainty a trend from the variogram even when elaborate methods of variogram estimation [e.g., Kitanidis and Lane, 1985] and model validation [e.g., Gambolati and Volpi, 1979; Kitanidis and Vomvoris, 1983] are applied. In view of this difficulty, one must look beyond purely statistical arguments for selecting one covariance model over another.

The behavior of the bromide tracer during the natural-gradient experiment provided the most useful information for discerning the presence or absence of a trend in the hydraulic conductivity field. A trend in the mean groundwater velocity at the test site was evident from the highly skewed tracer distribution exhibited along the longitudinal dimension of the plume. The borehole flowmeter measurements indicate that the large-scale variation in velocity was a direct consequence of the contrast between the hydraulic conductivities of the near-field and far-field regions of the site. The low conductivity present in the near-field region was responsible for what was essentially a delayed release of the tracer into the more permeable sediments present in the far-field. In our judgment the change in the overall groundwater velocity regime of the site produced by spatial variations in hydraulic conductivity constituted a trend, and that the third-order polynomial trend and associated covariance parameters provided the best representation of the hydraulic conductivity covariance.

To appreciate the degree of heterogeneity of the Columbus site a comparison of the variance of log hydraulic conductivity estimate for the Columbus site and seven other extensively investigated fluvial sites are given in Table 3. Because, in general, the observational scales associated with a set of hydraulic conductivity measurements may affect the variance estimate, the measurement scale and overall study scale are presented along with each variance estimate for consideration. Even allowing for differences in observational scales, it is evident that the Columbus site is one of the most heterogeneous sites investigated to date. In particular, we note that the $\sigma^2_{\ln K}$ for the Columbus site is approximately an order of magnitude larger than values estimated for the Borden and Cape Cod tracer test sites, both of which have measurement scales similar to Columbus.
### TABLE 3
Comparison of Log Hydraulic Conductivity Variance Estimates for Columbus and Seven Other Sites [after Boggs et al., 1990]

<table>
<thead>
<tr>
<th>Aquifer</th>
<th>$\sigma_{lnK}^2$</th>
<th>Approx. K Meas. Scale</th>
<th>Study Scale</th>
<th>K Meas. Method</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>alluvial sand and gravel (Columbus)</td>
<td>4.5^c, 2.8^d</td>
<td>15cm(v)</td>
<td>250m</td>
<td>flowmeter</td>
<td>Boggs et al., [1990]</td>
</tr>
<tr>
<td>outwash sand (Borden)</td>
<td>0.29</td>
<td>5cm(v)</td>
<td>20m</td>
<td>permeameter</td>
<td>Sudicky [1986]</td>
</tr>
<tr>
<td>outwash sand (Cape Cod)</td>
<td>0.26</td>
<td>15cm(v)</td>
<td>22m</td>
<td>flowmeter</td>
<td>Hess [1989]</td>
</tr>
<tr>
<td>silty clay loam, alluvium</td>
<td>0.4</td>
<td>5cm(h)</td>
<td>6m</td>
<td>infiltrometer</td>
<td>Sisson and Wierenga [1981]</td>
</tr>
<tr>
<td>Yolo loam, alluvium</td>
<td>0.9</td>
<td>46cm(h)</td>
<td>160m</td>
<td>infiltrometer</td>
<td>Vieira et al., [1981]</td>
</tr>
<tr>
<td>glacio-fluvial</td>
<td>0.8</td>
<td>100m(h)</td>
<td>5000m</td>
<td>pump test</td>
<td>Devary and Doctor [1982]</td>
</tr>
<tr>
<td>fluvial sand</td>
<td>0.9</td>
<td>7cm(v)</td>
<td>15m</td>
<td>grain size</td>
<td>Byers and Stephens [1983]</td>
</tr>
<tr>
<td>alluvial sand and gravel</td>
<td>1.5-3.7</td>
<td>1m(v)</td>
<td>150m</td>
<td>flowmeter</td>
<td>Hufschmied [1986]</td>
</tr>
</tbody>
</table>

Notes: a. The dimension of the measurement scale is given after each value; h = horizontal, v = vertical.
b. The horizontal dimension of study scale is given in each case.
c. Based on measured (undetrended) data.
d. Based on third-order polynomial detrended data.

### ESTIMATES OF HYDRAULIC CONDUCTIVITY VARIABILITY FROM OTHER METHODS

A comparison of the lnK covariance parameters estimated from the borehole flowmeter measurements and those obtained from the other conductivity measurement methods is given in Figure 10. Note that the covariance parameter estimates for the flowmeter were based on the measured (undetrended) data set. The relatively small samples associated with the secondary measurements precluded a meaningful nonstationary covariance analysis of these data, therefore, only stationary variogram analyses were performed.
The $\sigma_{\ln K}$ estimate of 2.9 for the grain-size conductivity estimates was outside of the confidence region about the $\sigma_{\ln K}$ derived from the stationary covariance analysis of the borehole flowmeter data. The disparity between these estimates could be due to several causes. The fact that approximately 45 percent of the grain-size based conductivity estimates were for core samples collected outside of the general region of the flowmeter measurements may partially account for the difference. It is also conceivable that the empirical formula of Seiler [1973] relating grain size to conductivity may not be accurate for the range of soil grain-size characteristics encountered at the test site. The horizontal and vertical correlation scale estimates from grain size compared favorably with the flowmeter-derived estimates. While the covariance estimates from grain size were highly uncertain because of the small sample size, it is encouraging to find that they lie within or close to the confidence intervals for the flowmeter estimates.

The $\sigma_{\ln K}$ of 1.8 estimated from slug tests was significantly lower than that estimated from the flowmeter data. This discrepancy was probably due to one or both of the following. First, the sample measurement scales of the two methods were different. The slug test produced an integrated conductivity estimate for a vertical section of the aquifer of 0.7 to 1.4 m in thickness, whereas the flowmeter conductivities were estimated for 15-cm thick layers. Therefore, a somewhat lower
variance would be expected from the slug test data. Second, because of the relatively short duration of the slug test (i.e., less than five minutes in most cases), the hydraulic conductivity estimate was representative of conditions in the immediate vicinity of the well screen. Consequently, the disturbed annulus created by auger installation of the piezometer may have significantly affected the conductivity estimate. The homogenizing effect of borehole disturbance would be expected to produce less variability in the resulting conductivity measurements obtained from the slug tests. Estimates of the horizontal and vertical correlation scales were not possible using the slug test data set due to the small number and low spatial density of measurements.

The results for the detailed hydraulic conductivity measurements obtained from laboratory permeameter testing of soil cores produced an estimated \( \sigma_h \) of 5.5. Although this value fell within the confidence interval for the flowmeter variance estimate, nothing conclusive can be said regarding the reliability of this method for estimating variability because all conductivity measurements were obtained from a single corehole. In addition, there were questions regarding the validity of a comparison of horizontal hydraulic conductivities measurements from the flowmeter test with vertical conductivity measurements from the permeameter test.

The correlation scales estimated from mapping of sedimentary facies in local gravel pits were only about 10 percent of those estimated from the flowmeter data. The reason for the discrepancy is not clear. One possible explanation is that the covariance structure of the aquifer exposed in the gravel pit is different from that at the tracer test site. Another explanation could be that the dimensions of the aquifer exposure in the gravel pit (approximately 20 m in length by 2 m in height) were too small to obtain representative facies measurements [Rehfeldt et al., 1989b].

The measurement grid spacings of 30.5 m and 15.2 m used in the DCR and SP surface geophysical surveys, respectively, were larger than the horizontal correlation scale estimated from the flowmeter data. Consequently, there were insufficient data to adequately define the horizontal scale, and only upper bound estimates of the horizontal scale equal to the smallest sample spacings could be estimated. An additional survey of the site using a measurement interval approximately 7 m would be needed to determine whether the DCR or SP methods can provide reliable estimates of the horizontal correlation scale [Rehfeldt et al., 1989b].

The secondary methods of directly measuring conductivity variations were substantially more expensive than the borehole flowmeter method. The cost of obtaining a single hydraulic conductivity measurement by the packer, permeameter, and slug test methods were approximately 3, 3, and 39 times, respectively, more expensive than the flowmeter method. It is interesting to note that the cost of conducting one large-scale aquifer test (e.g., AT2) which produced a single estimate of large-scale mean hydraulic
conductivity, was the same as that for obtaining approximately 1400 small-scale measurements of conductivity using the flowmeter method. The aquifer test has been used extensively in the past for characterizing the hydraulic conductivity field for solute transport predictions. Yet we now understand that transport predictions based solely on the mean hydraulic conductivity can be highly inaccurate [e.g., Gelhar, 1986], and that it is the hydraulic conductivity variability which largely controls transport at the field scale.

SUMMARY AND CONCLUSIONS

Several methods for obtaining direct or indirect estimates of hydraulic conductivity variability were evaluated at a natural-gradient tracer test site located at Columbus Air Force Base in Mississippi. The borehole flowmeter method was shown to be the most practical and effective technique for measuring hydraulic conductivity variability, and provided the primary data base for estimation of the spatial covariance of hydraulic conductivity. The variance ($\sigma_{\ln K}^2$) and the horizontal and vertical correlation scales ($\lambda_h$ and $\lambda_v$, respectively) were initially estimated directly from the natural logarithm of the hydraulic conductivity measurements assuming second-order stationarity of the conductivity field. Best estimates for $\sigma_{\ln K}^2$, $\lambda_h$, and $\lambda_v$ of 4.5, 12, and 1.5, respectively, were obtained. Approximate 95 percent confidence intervals of 3.4 to 5.6 were estimated for $\sigma_{\ln K}^2$, 7.3 to 21 m for $\lambda_h$, and 0.9 to 2.5 m for $\lambda_v$. It was not clear from the sample variograms whether the hydraulic conductivity field was, in fact, stationary; therefore, a nonstationary covariance analysis was performed to determine if data detrending would produce a significantly different set of covariance parameters. The method of weighted least-squares was used to fit three-dimensional polynomials of orders 1, 2 and 3 to the log conductivity measurements. Each polynomial trend was numerically removed from the measured data, and a variogram analysis performed on the log conductivity residuals. The third-order polynomial trend was judged the best representation of the conductivity drift based on its compatibility with the groundwater flow field inferred from plume observations during the natural-gradient tracer test. Best estimates for $\sigma_{\ln K}^2$, $\lambda_h$, and $\lambda_v$ of 2.8, 5.3 m, and 0.7 m, respectively, were calculated from the order-3 detrended data. The covariance parameter estimates for detrended data were below the bounding values obtained from the measured data indicating a significant difference between the two sets of parameters. Examination of the variograms for the measured and detrended data sets failed to establish with certainty the presence or absence of a trend. However, the large-scale spatial variation in mean groundwater velocity indicated from the tracer experiment, which was shown to be a direct consequence of the contrast between the mean hydraulic conductivities in the near-field and far-field regions of the test site, constitutes a trend. We conclude that, within the confines of the tracer experiment, a trend is indicated, and that the third-order polynomial trend and associated variance and correlation scales provide the best representation of the hydraulic conductivity covariance.
The results of the spatial covariance analysis for the Columbus site have general implications for practical applications involving heterogeneous aquifers. First, it is important to note that without the tracer plume observations it would have been difficult to establish with certainty the presence of a trend in the hydraulic conductivity field at the site. In practical situations tracer test results are not likely to be available to aid in discerning a conductivity trend. One must rely more heavily on interpretation of the log conductivity variograms and on other physical information regarding the aquifer, such as the major geologic features or the phreatic surface configuration, for identifying drift in the conductivity field. Second, there was large uncertainty associated with the estimated covariance parameters despite the large number (2187) of conductivity measurements used for parameter estimation. This result indicates that parameter uncertainty will be inevitable for practical problems.

The experience with the borehole flowmeter method shows the feasibility of observing the hydraulic conductivity covariance parameters required for stochastic models of macrodispersion, even though the covariance parameters may be subject to uncertainty. The availability of a practical technique for acquiring extensive hydraulic conductivity measurements in three dimensions also suggests the possibility of applying more deterministic advection-based transport models in the future.

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REFERENCES


