OBSERVATION SCALE EFFECTS ON

FLUID TRANSPORT BEHAVIOR OF SOIL

by

Karen A. Albrecht

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APPROVED:

J. C. Parker, Chairman

T. B. Hutcheson, Jr., Head

J. C. Baker

R. B. Reneau Jr.

T. W. Simpson

N. L. Powell

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(ABSTRACT)

Variabilities of hydraulic and solute transport properties of soil are examined at three scales: pore-scale, sample volume-scale, and field-scale. Undisturbed soil cores were taken at 19 subsites spaced logarithmically along a 150 m line transect in a Groseclose mapping unit near Blacksburg, Virginia. Three core sizes were taken at each subsite at the soil surface and 0.5 m depth. 'Small' cores were 40x54 mm; 'medium' cores were 60x100 mm; and 'large' cores were 100x150 mm. Macropore effects on solute transport were evaluated using monocontinuum and bicontinuum models. Bicontinuum-predicted solute breakthrough curves (BTC) closely agreed with observed BTC data with mean errors of reduced concentrations ≤0.05 for 97% of the samples. Monocontinuum predicted BTC's had comparable fits with 80% of the samples having mean errors ≤0.07. The simpler monocontinuum model was chosen for estimating dispersion coefficients for all samples on the basis that seven percent error

in concentration is acceptable for the purpose of making field predictions in light of high spatial variability. Sample volume did not significantly affect the low variation (coefficients of variation (CV) of 7-20%) soil properties bulk density or moisture retention characteristics in Ap or Bt horizons. Large cores are recommended for assessing high variation (CV of 60-280%) fluid transport parameters, saturated hydraulic conductivity (K_s), pore water velocity and dispersion coefficients (D) since they yielded less variance than the smaller cores. Ranges of about 25 m were determined for log-transformed K_s and D from semivariograms. Monte Carlo simulations were used to predict field-average BTC's.

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INTRODUCTION

Half of the population of the United States relies on groundwater as a source of drinking water (Miller, 1980) and use is increasing at a rate of 25% per decade. Current data indicate that there are at least 17 million waste disposal facilities dumping over 6.5 billion cubic meters of contaminated liquid into the ground each year. Geologists have found that organic solvents spilled on the land remain in the soil zone for tens of years gradually leaching toward the water table. The potential for large-scale groundwater contamination is apparent. Hazardous waste sites number over 15,800 in the U.S. with only 418 targeted for cleanup (Gorelick and Voss, 1984). Assessment of human health risks and economic factors require examination of water and solute transport processes through contaminated soil. Understanding of these processes is also fundamental in managing agricultural problems such as deficient moisture supply, salinity, and leaching of applied fertilizers, pesticides and wastes.

Scale of observation strongly influences hydraulic and solute transport characteristics of soil (Peck, 1983). Solute transport parameters measured in the laboratory may lead to erroneous predictions of field behavior if scale effects are not explicitly considered. At the laboratory scale scientists have found it difficult to adequately describe dispersive transport in aggregated soils (Biggar and Nielsen, 1962; Rao et al., 1980; Nkedi-Kizza et al., 1982). Size and arrangement of peds under field conditions is probably the main problem, however part of this difficulty may also lie in the use of inappropriate boundary conditions when solving the convective-dispersive equation. Parker and van Genuchten (1984a) and van Genuchten and Parker (1984) point out the incongruity of using volume-averaged concentrations at the soil column exit where concentrations are necessarily flux-averaged. Bicontinuum models may be necessary to adequately describe transport in soils with macropores.

Transport properties are often observed to vary with scale of observation beyond the pore domain. Solute dispersivities in aquifers increase with increasing distance from the injection source (Gelhar et al., 1979, Dieulin et al., 1981, Smith and Schwartz, 1980; Matheron and DeMarsily, 1980; Pickens and Grisak, 1981; Leland and Hillel, 1982, Sudicky et al., 1983). Infiltration estimates are dependent on sample volume with larger diameter cores providing more accurate infiltration estimates (Sisson and Wierenga, 1981). Limited research has been reported which compares the effects of sample dimensions on hydraulic and solute behavior in soil.

At the field-scale hydraulic conductivity and dispersion coefficients exhibit spatial dependence and lognormal population distributions (McIntyre and Tanner, 1959; Nielsen et al. 1973; Baker and Bouma, 1976; Cameron, 1978; Warrick and Nielsen, 1980). This scale-dependence raises questions regarding numbers of samples and spacing between samples to provide an optimum representation of the field. Progress has been made in the application of geostatistical methods to determine optimal spacing between samples and stochastic models have been developed to describe transport in heterogeneous fields (Peck et al., 1977; Warrick et al., 1977; Simmons et al., 1979; Gelhar, 1982; Amoozegar-Fard et al., 1982).

The objectives of this study are to:

1. evaluate effects of macropores on solute transport in soil and compare monocontinuum and bicontinuum approaches;
2. evaluate the effect of soil core dimensions on saturated hydraulic and solute transport parameters; and
3. characterize the field-scale heterogeneity of hydraulic and solute transport parameters.

Results from this study will provide useful information pertinent to the analysis of solute dispersion in field soils.

REVIEW OF LITERATURE

MACROPORES

Soil heterogeneities at the pore-scale, at the field-scale,and at intermediate scales pose problems for the evaluation of water and solute behavior in soils (Burrough, 1983a,b). At the pore-scale, variations in pore size, shape, continuity, connectivity, and tortuosity strongly influence fluid transport phenomena. Macropore effects are especially important since large pores offer paths of low resistance and often induce preferential fluid flow through only a small fraction of the porous medium (Wild and Babiker, 1976; Bouma, 1981; Beven and Germann, 1982; Bouma et al., 1983). Thomas and Phillips (1979) reviewed macropore effects and point out that macropore flow may be significant even in unsaturated conditions where transport may occur in thin films along pore walls. Wild and Mazaheri (1980) reported field studies in which leaching of solutes was much slower than predicted using leaching depths calculated from net infiltration divided by volumetric water content. After 10 weeks they concluded that short-circuiting of rain through the wide channels occurred too fast to equilibrate with the solution in the soil matrix. Sidle and Kardos (1979) applied liquid sludge to a clay loam field and observed accelerated nitrate leaching over a six month period. Miscible displacement data on undisturbed soil cores confirmed rapid breakthrough of chloride. Macropore channeling was responsible and an 'average active transmitting porosity' of about 15% was calculated using a water budget modeling approach. About half of the pores were determined to be stagnant.

Classification of macropores by size is presently debated. Suggestions are as varied as they are numerous (Bouma, 1981). Beven and Germann (1980) suggested defining macropores as those pores with radii >2 mm (with corresponding tension of 0.01 m). Johnson (1960) proposed defining macropores as ≥0.75 mm diameter (with corresponding tension of 0.4 m). Bouma (1979) advised that pore continuity is more important than size since continuous pores of 0.4 mm diameters were found to conduct significant volumes of fluid. He offered a vague definition for macropores as those significantly larger than pores resulting from simple soil particle packing. Ambiguity surrounding this term has been commented on by many scientists. No clear definition exists. Data by Germann et al. (1984) agree with Bouma's hypothesis that pore continuity is more important than pore size. Germann et al. infiltrated a solution of KBr with Alizarin Red S dye in the field using large (0.3x0.3x0.5 m) in-situ resin coated soil cores. Worm holes, insect burrows, and root channels stained red while pores of similar size and geometry in the same layers remained unstained confirming that continuity and connectivity are more important than size. Root channels were continuous down to 0.4m and ant channels about 5 mm diameter were continuous from the surface to about 0.25 m depth. Scotter (1978) determined what he called a 'critical' size macropore as the smallest continuous pore that still induces channeling. From a theoretical analysis, he suggests that if pores are continuous they only need to be about 0.1-0.2 mm diameter to induce channeled fluid transport. Highly idealized soil-void geometries were assumed.

Few field data quantifying macropores are available for comparison. Kanchanasut et al. (1978) observed 3 mm wormholes in undisturbed cores. Simpson and Cunningham (1982) reported thorough descriptions of channels (distinguished from macropores as paths of loosely-packed soil) in a clay soil used for waste-water irrigation. Channels ranged from about 10-600 mm diameters and tapered with depth into the B horizons. Channels contained many 10 mm diameter continuous macropores. Saturated hydraulic conductivities were 4-18 times greater in channels than in the soil matrix. Flow was determined to occur primarily in channels which occupied less than 10% of the soil volume. Doubts were cast on this soil's attenuation capacity.

Solute movement in soil occurs by convection, dispersion (mixing due to pore-scale variations in fluid velocities) and diffusion. This phenomenon can be described for steady-state flow of an inert solute in a one-dimensional, homogeneous, porous medium by the convection-dispersion equation (CDE):

$$\frac{\partial c}{\partial t} = D\frac{\partial^2 c}{\partial x^2} - v\frac{\partial c}{\partial x} \qquad [1]$$

where c is concentration, t is time, x is distance, v is the average pore-water velocity (flux divided by volumetric water content), and D is the dispersion-diffusion coefficient (hereafter referred to simply as the dispersion coefficient). Reactive solutes are accounted for by adding a source/sink term. Analytical solutions for specific initial and boundary conditions and numerical solutions for more general conditions are present in the literature. When matched with miscible displacement data, these solutions predict concentration distributions and breakthrough curves (BTC's). Disperison coefficients may be derived from the BTC by inversion of appropriate solutions of Eq. [1]. Values are dependent on pore-water velocity and on pore structure. Increasing heterogeneity both at the pore-scale and at the field-scale increases the value of D.

Equation [1] describes the porous medium as a simple continuum, ie. v and D are values averaged over the entire soil volume. Problems arise with the monocontinuum approach in aggregated media. Miscible displacement studies show strongly nonsigmoidal and asymmetrical BTC (Rao, 1976; Bouma and Wosten, 1979) as opposed to the typical sigmoidal BTC for narrow pore size distributions which yield relative concentration of close to 0.5 at one pore volume. Failure of the CDE has been suggested by many researchers (Quisenberry and Phillips, 1976, 1978; van Genuchten and Wierenga, 1976, 1977; Gaudet, 1977; van Genuchten and Cleary, 1979; Bouma and Wosten, 1979). Quisenberry and Phillips applied small pulses of water and chloride in a field with a volumetric moisture content (θ)<field capacity. Water and chloride travelled much faster than predicted suggesting little displacement of the initial solution. Little radial diffusion occurred due to rapid channeling especially below the Ap horizon. Half of the pore space behaved as an immobile zone. Van Genuchten and Cleary (1979) conclude from such results that the CDE may be inadequate to describe leaching of aggregated soils and suggest that when such large fractions of stagnant water are present that a two-region or bicontinuum approach may better describe transport phenomena.

Two-region models partition soil water into a mobile region where transport occurs mainly by convection and an immobile region where transport is governed by diffusion. Wagenet (1983) reviews some of these models (Philip, 1968; Edwards et al., 1979; Hoogmoed and Bouma, 1980; Beven and Germann, 1981). Nkedi-Kizza et al. (1983) categorize two-region models by their different assumptions regarding the exact form and location of the stagnant water in the system. One group of models considers stagnant water as films surrounding soil particles where solute transport is described by Fickian diffusion into and out of the films (Skopp and Warrick, 1974). Film thickness is curve-fitted to the BTC data. Skopp and Warrick derived a simple solution by assuming transport in the mobile zone was only by convection and neglected dispersion.

Another group of two-region models regards stagnant water as that inside aggregates plus films covering aggregates (Lapidus and Amundson, 1952); in this case aggregate size and shape and film thickness must be evaluated. Passioura (1971) derived a longitudinal D value using aggregate size and pore water velocity. Results indicated that this 'lumped-parameter D' approach was valid for limited conditions. Rao et al. (1980) confirmed Passioura's findings by describing solute BTC's in synthetic aggregated media.

Another approach considers all inter-aggregate water as mobile and stagnant water as exclusively within aggregates (Nkedi-Kizza et al (1982). Geometry estimates of the immobile region were employed. Skopp et al. (1981) used a bi-continuum approach with both regions considered as mobile with a linear transfer function.

Instead of categorizing two-region models by stagnant water location as Nkedi-Kizza suggest, it may be more meaningful to distinguish how models define the mass rate of solute exchange between mobile and immobile regions. Commonly an empirical linear or first-order rate constant is used. Exchange is assumed to be proportional to the concentration difference between the two phases. Petroleum engineers Coats and Smith (1964) developed a model of this type for nonreactive solutes. Twelve years later, van Genuchten and Wierenga (1976) employed a similar approach to describe movement of adsorbed solutes through aggregated soils. Researchers have complained that the two-region approaches have been mostly empirical and point out that what has been missing are physically measurable properties related to transport phenomena. Aggregate size and shape effects were discussed by Passioura (1971) and Rao et al. (1980).

Recently van Genuchten (1985) proposed a two-region model which considers size and shape of aggregates. Theoretically derived shape factors dependent on aggregate geometry are utilized to transform the aggregate into an equivalent sphere. The soil system is treated as an ensemble of uniformly-sized spherical aggregates. Diffusional transfer of solute between mobile and immobile regions is assumed yielding a nonlinear transfer function. Good accuracy is obtained for hollow cylindrical macropores, but much less for plane-sheet type aggregates. The model is considerably more accurate than a linear kinetic model, however, and in view of the uncertainty in pore geometry in the field, the equivalent sphere model is suggested as being of satisfactory accuracy.

Extreme approaches have also been tried. Rao et al. (1976) used a capillary bundle model, but the model failed to describe experimental BTC's when the pore-size distribution calculated from moisture retention data was used as input. No interaction between streamtubes was the major limitation of this approach. Importance of pore interconnectivity was confirmed. Scheidegger (1954) tried a pore structure model for completely random structure. Solute transport was described in a manner analagous to Einstein's theory of Browian motion. Results expectedly deviated from reality.

Although these two-region models may be physically valid, they have the undesirable attribute of increasing the number of parameters which must be evaluated by elaborate curve-fitting methods (van Genuchten and Cleary, 1979). Parker and van Genuchten (1984) suggest that in certain cases a monocontinuum approach may be used for fractured porous media provided appropriate boundary conditions are used. Two types of boundary conditions (BC's) for semi-infinite systems were commonly used in previous studies. Dirichlet or first-type upper BC's specify $c=c_o$ at the column inlet and implies flux-averaged concentrations. These conditions adequately predict BTC's for finite columns, but do not reflect the real solute distribution in the core. Cauchy or third-type BC's stipulating solute flux at the inlet yield volume-averaged concentrations in the porous media. Solute distributions are more accurately reflected, but predicted BTC's are erroneous. Petroleum and chemical engineers have recognized the importance of appropriate BC's in solving miscible displacement problems for some time (Brenner, 1962) however the necessity of stipulating flux-averaged concentrations for effluent from a finite column was not realized until the work of Brigham (1974) and Kreft and Zuber (1978) who showed that this distinction between flux- and volume-averaged concentrations becomes increasingly important as

Peclet numbers decrease as is the case with soils with macropores. Soil physicists working independently reached the same conclusion (Parker and van Genuchten, 1984). Parker and van Genuchten in a series of studies (1984a,b; van Genuchten and Parker, 1984; Parker, 1984) show that flux-averaging is the only meaningful way to interpret soil column effluent concentrations. Use of proper boundary conditions is critical to correctly evaluate BTC of porous media containing macropores. Breakthrough curves for a packed sand column containing a 1.7mm diameter 'wormhole' were predicted accurately by both equilibrium and two-region models. Concentration distributions determined from the sectioned core confirmed that the third-type upper boundary conditions yielded resident concentrations.

A few attempts have been made to compare monocontinuum models with two-region models. Davidson et al. (1980) compared the two-region aggregate model of van Genuchten and Wierenga (1976) with Lindstrom's (1967) monocontinuum model (using θ=0.40, P=1.3) for soil column leaching data. Predicted BTC's were almost identical. Therefore the simpler model of Lindstrom's is preferable to the complex two-region one. Difficulty of assessing appropriateness of different models is emphasized by the authors, especially when they may yield similar results in certain cases. Another model comparison was made using the data of Davidson and McDougal (1973). Picloram (4-amino-3,5,6- trichloropicolinic acid) was displaced at two velocities (0.15 and 1.32 md^{-1}). The one-site equilibrium model (van Genuchten et al., 1974) was only valid for the lower velocity (the reaction rate must be 'fast enough' with respect to the fluid flow rate). Reasonable BTC's were calculated for both velocities with the two-site nonlinear, nonequilibrium adsorption model of Selim et al. (1976), but at the lower velocity the equilibrium model described the data better. This suggests that in certain cases the simpler equilibrium models may suffice in lieu of nonequilibrium models. Conversely there are certain situations where the monocontinuum approach fails and the additional complexity of a bicontinuum is necessary.

Verification of physical models is a difficult task. Goodness-of-fit between model simulations and experimental data is generally used as a criterion for model verification, but Davidson et al. (1980) point out the large uncertainty in many parameters which are estimated by the same curve-fitting technique used to judge model accuracy. Van Genuchten et al. (1984) suggest that "this is a problem that raises questions not only with respect to parameter uniqueness and model verification, but also with respect to the usefulness of these models in ultimately predicting solute transport in structured field soils". Rao et al. (1979) imply that physically measurable paramaters related to transport phenomena may ameliorate this problem. Valocchi (1985) proposes a threshold criterion where local equilibrium models fail and two-site (diffusion and linear) kinetic models are necessary. Using time moment analysis he defines the index as the fractional change in the variance and skewness moments for equilibrium and kinetic models. The index is a relative measure of moment differences with respect to the absolute value of one of the moments. Bulk flow, equilibrium sorption, and kinetic sorption parameters influenced its value.

SAMPLE VOLUME

Field experiments are a desirable means of characterizing hydraulic properties and solute behavior of soils and gaining direct information on natural variability. Unfortunately in-situ tests are often expensive and prone to considerable error if not performed with great care. Alternatively many 'small' cores are sampled, analyzed in the laboratory and results are interpreted as being representative of a large area. Inherent problems in this procedure are whether tested samples are truly representative and whether changes have been induced by physical disturbance.

Fundamental to the heterogeneity problem is the continuum concept. Most soil properties cannot be measured at a single point since any point may fall either in the solid component or the void space. Measured quantities are taken as averages over some sample volume with the measurement 'point' corresponding to its centroid; the magnitude and dimensions of this volume are critical. Bear (1975) defines a representative elementary volume (REV) as being sufficiently larger than the the size of a single pore that it includes an adequate number of pores to permit a meaningful statistical average, but small enough to avoid averaging out information which we want to observe. The REV is the smallest sample that yields a constant variance due only to experimental error of a specific soil property. Because of its dependence on local pore variation, the size of the REV will depend on the homogeneity of individual soils and the soil property of concern.

Intuitively 'large' samples incorporate more of the field variability than 'small' samples so it can be expected that between-sample variance will be less for large cores. Consequently fewer samples are needed to obtain the same level of accuracy. Several studies support this hypothesis. Ball and Williams (1968) evaluated variability of soil chemical properties. Three sites were located about 27 m apart with 3 groups per site along a 260 m transect and with 2 samples per group. Large samples 0.3x0.3x0.15 m and small samples 0.07x0.07x0.15 m were taken using a graduated straight-sided trowel. Coefficients of variation (CV's) for exchangeable cations (K, Ca, Mg, Mn) and extractable P_2O_5 were much higher for small samples (28-48%) than for large samples (4-13%). Numbers of samples needed to give mean values within 10% at the 0.05 level emphasize this difference in variation. About 30 times more small samples would have to be taken than large ones for exchangeable cation analysis and about 100 times more small samples would have to be taken for extractable P_2O_5. This shows that by incorporating more of the field heterogeneity larger samples will yield lower variance and require fewer samples for equivalent accuracy.

Sample volume effects on soil moisture measurements were determined by Hawley et al. (1982). Disturbed cores were taken from a small 2 m^2 'homogeneous' area. Eight core sizes ranging from 7 to 825 cm^3 were compared; F-tests on the variances revealed that 'small' samples (less than 50 cm^3) had significantly greater variance at the 0.01 level than 'large' cores (50 cm^3 or greater). Analysis of variance on the large cores showed no significant differences implying that these samples were representative of the same true population. They concluded that the minimum desirable sampling volume for soil moisture content for the Beltsville area to be about 50 cm^3 and that smaller volumes will give less accurate estimates than larger ones. Due to the uniformity of the area studied it is likely that the minimum desirable sampling volume in other situations may be larger.

Hassen et al. (1983) studied the dependence of measured soil properties on sample volume. A field solute tracer experiment was conducted by applying ten centimeters of water containing 1000 mg/L of chloride as $CaCl_2$ over 5 days on five 1.5 m^2 plots. Samples were taken after a 5 day equilibration period with samplers of two sizes. The larger sampler was a bucket auger with a 79 mm inner body diameter and cutting edge diameter of 90 mm. The smaller sampler was a "Veihmeyer" tube with a 21 mm cutting diameter. Large and small samples were taken only a few centimeters apart laterally at 100 and 200 mm increments down to a depth of 1.6 mm. Higher chloride recoveries (63.4 mg Cl^-/kg soil) and larger variations (CV of 16%) were observed for smaller samples than for larger ones (51.4 mg Cl^-/kg soil with CV of 8%). Solute profile distributions for both sizes were similar except smaller samples had greater standard deviation. Comparing variances of concentrations at different depths, small samples had the highest CV of 199% at the 1.4-1.6 m depth while the highest CV of the large cores was 54% at the 0.7-0.8 m depth. Errors discovered during mass input/recovery calculations were blamed on soil disturbance generated using augers as sampling devices. Since disturbance is a major factor influencing accuracy of measured values it bears emphasis. Because the large samples apparently recovered 1.83 times more Cl^- than was added, it was inferred that augers must have a larger mean effective diameter of 97.6 mm due to lateral cutting in the bore hole. The small push probe yielded recovery values near the added chloride mass, but the effective diameter was calculated as being a smaller 19.3 mm due to compaction and friction excluding some soil as the tube fills thus increasing the effective depth. Generally large sample volumes are endorsed, but not without reservations regarding various sampling techniques.

Sisson and Wierenga (1981) measured steady-state insitu infiltration rates at three scales using rings with 0.05, 0.25, and 1.27 m inside diameters. Their field plot layout consisted of placing large rings within a 635 cm^2 area in a 5x5 matrix, then putting five medium rings in each large ring and four small rings in each medium ring; this arrangement yielded a combination of 25 transects. Serial irrigations and drainage were performed for 2 weeks prior to the experiment. Then the field was ponded continuously with a 30 mm head for 3 days to ensure steady-state conditions before infiltration rates were measured. Cumulative frequency distributions of log-transformed infiltration rates showed large and medium rings yielding nearly identical means (2.12 and 2.00) with higher variance in medium rings (0.0516 versus 0.2744). Small rings exhibited a mean and variance of 1.68 and 0.405 respectively and had distributions which were more skewed than that of a lognormal distribution. Results show that variances of infiltration rates decrease rapidly with increasing ring diameter.

Peck (1983) states that variances of observations will usually decrease as core size increases. He comments on the study by Sisson and Wierenga (1981) saying that it appears likely that even the largest ring was still smaller than the REV for the authors' soil. Peck further asserts that spatial variation of soil properties may be such that an REV does not exist or it may be larger than any practical sample. Systematic trends in means or variances of soil properties may account for this; i.e. differences in means or variances from one area to another in a field.

Nielsen et al. (1983) illustrate the effectiveness of different sample volumes for representing solute distributions in soils with macropores. They show idealized autocorrelograms for large and small cores showing the integral scale (λ) of the small cores to be much smaller than the λ of the large cores. Small λ for small cores is interpreted as spatial independence with only a few of the small cores actually sampling the solute travelling through the macropores while most cores completely miss the macropores. This results in high variance and little confidence that small core means are reflective of the true mean. Values of λ several times greater than the diameter of the sample for large cores is interpreted as cause to take fewer samples since the large cores contain more macropores and exhibit concentration distributions which have lower variance.

There are few published studies quantifying sample volume effects on soil properties and most of these are limited in scope by the sampling techniques used or the specific property tested. Results of Hawley et al. (1981) and Hassan et al. (1983) cannot be appropriately extrapolated to undisturbed sample dimensions since the sampling devices generated so much disturbance. Sensitivity of the particular soil property being evaluated to heterogeneity is also an important consideration. Soil moisture characteristics do not vary much -- common CV's are between 10-30% (Warrick and Nielsen, 1980). Chemical properties measured by Ball and Williams (1968) had CV's less than 50%. Flow parameters, because of their strong dependence on pore size distribution, may be significantly influenced by the dimensions of the sample measured and are most sensitive to field heterogeneity with CV's generally well over 100% (Warrick and Nielsen, 1980) for saturated hydraulic conductivities (K_s), dispersion coefficients (D), and pore water velocities (v). There is only one study to this author's knowledge on sample volume effects on flow parameters in soil (Sisson and Wierenga, 1981).

FIELD-SCALE SPATIAL VARIABILITY

During the past decade soil spatial variability has received much attention. Classical statistical approaches are unable to adequately treat spatial variability since neighboring samples may not be independent of each other. Samples taken close together tend to be more similar than those taken far apart (Mader, 1963; Beckett and Webster, 1971; Nielsen et al., 1973; Webster, 1977). Field-scale variations of hydraulic properties have been observed to follow a structured arrangement associated with relief, parent material, and soil-forming processes. Keisling et al. (1977) observed that variance of hydraulic conductivity was less when sampling was restricted to a 'small' land area of 5.6 km radius as opposed to a 'large' land area of 7.3 km radius. Shumway (1984) reviews methods available for analyzing spatially correlated data. The relationship between variance of flow properties and distance between samples may be described by means of autocorrelograms (Lumley and Panofsky, 1964; Russo and Bresler, 1981a,b; Sisson and Wierenga, 1981; Gajem et al., 1981) or semivariograms (Delhomme, 1978; Luxmoore et al., 1981; Yost et al.,1982a,b; Russo and Bresler, 1982).

Semivariogram analysis has the advantage over autocorrelation methods of not assuming second-order stationarity constraint which may not be realized in many soil systems. Details regarding these geostatistical methods are presented by Journel and Huijbregts (1978). Semivariance, which is proportional to the squared differences between values of two data points separated by some lag distance, is plotted as a function of the separation distance. Typically there is an initial rising portion of the curve corresponding to some spatial dependence (adjacent samples are more alike than those taken far apart) and gradually the curve flattens and reaches a constant finite population variance, called the sill where observations are random. Spatial independence is usually obtained at large separation distances. Distance to the sill is termed the range and reflects the largest average sample separation distance over which a parameter is correlated with itself or the minimum distance to ensure random sampling. Nuggets (semivariance values >0 at zero lag) are often observed. Journel and Huijbregts (1978) attribute these to measurement errors and random white noise due to micro-variabilities not distinguished at the scale observed. Burrough (1977) showed that what may be regarded as noise at one scale is revealed as structure at a different scale.

Semivariograms are touted as having the advantage of applicability in cases with sparse data (Shumway, 1984 and Gelhar, 1982), but Gelhar points out that ranges estimated in this manner are subject to much uncertainty. And what is meant by sparse data? One hundred samples are commonly recommended as minimal, but stable graphs may not even be obtained with 200 points (Bakr, 1976). Other problems with variograms are pointed out by Peck (1984). In some cases semivariance never levels off so it is impossible to define the range (Hajrasulika et al., 1980; Gajem et al., 1981;

Luxmoore et al., 1981). Nested structures of variation (the combination of several sources of variation operating on different spatial scales, for example worm activity versus topography) may be obscured in conventional variograms. Burrough (1983) proposed the use of stochastic fractals to resolve pertinent details; this involves assigning weights and scales to each effect before calculating the semivariogram. Armstrong (1984a,b) describes the often erratic nature of semivariograms and some of the problems associated in their construction and interpretation such as poor choice of distance classes, mixed data from two statistical populations, outliers, and skew distributions. Much literature is now available on the spatial structure of variance of hydraulic properties, but few studies provide adequate field data and few are reported for solute transport parameters.

Applications of schemes relating lab measured parameters to field systems may be misleading if these heterogeneities are not accounted for. This problem is commonly approached by using stochastic models to make field predictions for water and solute transport. Monte Carlo simulations have been used by many investigators (Freeze, 1975; Tang and Pinder, 1976; Peck et al., 1977; Amoozegar-Fard et al., 1982). Historically the term 'Monte Carlo' was introduced by Los Alamos workers as a code word for their secret work during World War II (Hammersley and Handscomb, 1964). It was suggested by the gambling casinos at the city of Monte Carlo in Monaco. Developed primarily for research on the atomic bomb, the method simulated random neutron diffusion in fissile material. Applications today are numerous. Basically, random values of a parameter(s) generated according to a specified probability density function (p.d.f.) are used to solve for the value of the desired parameter for each random value and a p.d.f. for the unknown may be estimated by averaging over the set of realizations. Variations of the technique are discussed thoroughly by Hammersley and Handscomb (1964) and Rubinstein (1981).

MATERIALS AND METHODS

FIELD METHODS

The field site was located in a Groseclose mapping unit at the Virginia Polytechnic Institute and State University Kipp's Farm Research Site near Blacksburg. Groseclose soils are classed as clayey, mixed, mesic Typic Hapludults and are deep and well drained with slowly permeable subsoils. They occur on nearly level to very steep convex ridges and sides-lopes in the Appalachian Valley and formed in materials weathered from interbedded limestone, shale, siltstone and sandstone. The Ap horizon is typically 0.25 m thick and has a loam texture with moderate fine granular structure. The Bt horizon typically extends from 0.25-0.70 m and has a clay texture with moderate very fine and fine subangular blocky structure. Mineralogical analysis shows a high presence of montmorillonite in these soils -- about one fourth to one third of the total clay fraction (42-76% clay from particle size analysis) may be montmorillonite between depths of 0.18-0.69 m.

Samples were taken in September of 1982 along a 150 m line transect spaced as shown in Figure 1. This scheme was selected to obtain information on variability at various scales over a relatively long transect with minimal sample

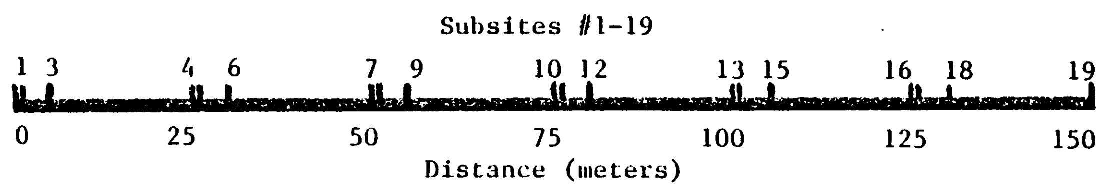

Figure 1: Sampling design showing 19 subsites spaced logarithmically along a 150 m line transect.

number. There were 19 subsites spaced so that there were 6 pairs of samples separated by 0.5 m, 6 pairs separated by 5 m, 6 pairs separated by 25 m, etc. The line transect ran due southwest of the first subsite which can be pinpointed as 76.5° west of north of the silo across Rt. 687 and 2° west of north of the first roof peak of the adjacent townhouses. There was a gradual 1-2% slope along the transect, inclining from subsites one to 19.

Three sizes of 'undisturbed' cores were taken at each subsite at the surface and at a depth of 0.5 m. We refer to these sizes for convenience as 'small', 'medium' and 'large'. Small cores were 40 mm long with 54 mm diameters yielding a volume of 9.2×10^4 mm^3; medium cores were 60 mm long with 100 mm diameters yielding a volume of 4.71×10^5 mm^3; large cores were 100 mm long with 150 mm diameters yielding a volume of 1.77×10^6 mm^3. As an indicator of probable disturbance, the ratio of sampler wall thickness to sample diameter was 0.071 for small cores, 0.013 for medium cores, and 0.023 for large cores. Small cores were taken in brass rings using a hydraulic sampler; medium rings of stainless steel and large rings of steel were driven into the ground by hand and then carefully dug out. Cutting edges of cores were beveled to minimize disturbance. Smearing at the ends was minimized by exposing fresh surfaces by chipping off small aggregates at natural fracture planes. Samples were stored at 4°C.

Before any samples were taken, infiltration was measured in the field at every subsite at each depth using the double-ring ponded infiltration method. Flux of 0.01 M $CaCl_2$ into the center ring was measured while maintaining a constant ponded head; the same head was maintained in the outer ring to minimize lateral flow in the center ring. Tensiometers were installed at a depth of 0.10 m in the outer ring to measure the hydraulic gradient. The test was run until steady-state was reached - either a constant flux or tensiometers indicating saturation. Saturated hydraulic conductivity (K_s) was calculated from the steady infiltration rate and the hydraulic gradient using Darcy's law. After the infiltration test, the inner rings were dug up and used as the large cores.

LABORATORY METHODS

In the laboratory, K_s was measured for most of the samples using the falling head method, but some high K_s samples were analyzed using the constant head method (Klute, 1965). Cores were assembled in Tempe pressure cells and tension wet slowly from the bottom for 1-2 days before inundating with a solution containing 0.01 M $CaCl_2$ and 2 ppm $CuSO_4$ to prevent clay dispersion and to control microbial growth respectively. Constant or falling head burettes were used at the Tempe cell inlet. Hydraulic gradients and fluxes were measured and K_s was calculated from the appropriate integration of Darcy's law.

Following K_s measurements, the samples were desorbed in the Tempe cells to a head equivalent matric tension (h) of 0.1 m by adjusting the outflow burette level. Final outflow volume and sample mass were recorded. Higher tensions of 0.5, 1.0, 3.0, 6.0, and 10.0 m were applied in a pressure chamber and corresponding amounts of water desorbed were measured gravimetrically. After moisture retention characteristics $\theta(h)$ were determined, miscible displacement tests were run. Final oven-dry masses for bulk density calculations were taken after the solute tracer tests. Bulk density was calculated in the usual manner. Large and medium rings which were not completely soil-filled were filled with sand of known bulk density to determine the core volumes.

Dispersion coefficients for bromide transport in saturated samples were determined by miscible displacement. Initially a constant ponded flux of a solution containing 0.01 M $CaCl_2$ and 2 ppm $CuSO_4$ was applied to soil cores via a mariotte device. After passing at least one pore volume of solution through the column or until flux became constant the supply was removed and when the free solution had disappeared from 50% of the soil surface a displacing solution containing 0.01 M $MgBr_2$ was applied. Bromide was selected as the tracer because it is generally not present in soil (Smith and Davis, 1974) and it is simple to analyze. Hydraulic gradients were kept close to 1.0. Effluent was collected in suitably small fractions over a range of 2-4 pore volumes. The concentration of Br^- in each fraction was measured to within a precision of 10 μM with an ion-specific electrode.

Average pore water velocities (v) were determined from the measured flow rates and saturated moisture contents. Dispersion coefficients (D) were estimated by fitting measured effluent concentrations to predictions for a monocontinuum model and a linear kinetic bicontinuum model for flux concentrations (Parker and van Genuchten, 1984b). The fitting procedure utilizes a nonlinear least-squares inversion method. Least-squares methods find the values of the constants in the chosen equation that minimize the sum of the squared deviations between observed and predicted values (SSQ). Differences between observed and predicted concentrations for specified pore volumes are termed residuals. In this study, reduced concentrations defined as $(c-c_i)/(c_o-c_i)$ are used, where c is the concentration of Br^-

in the effluent, c_i is the initial concentration of Br^- in the soil, and c_o is the concentration of Br^- in the feed solution. A reduced concentration of one corresponds to an actual concentration of 10,000 µM Br^-. Residuals are all expressed as fractions. As a criterion to compare goodness-of-fit between monocontinuum and bicontinuum models a 'mean error' is defined as $(SSQ/n)^{\frac{1}{2}}$ where n is the number of observations of pore volume-concentration pairs.

Dispersivities (ε) and Peclet numbers (P) were calculated for the monocontinuum model as

$$\varepsilon = D/v \qquad [2]$$

$$P = vx/D \qquad [3]$$

where x is the column length. Note in the Bt horizon a different set of small cores was used to run miscible displacement tests on than was used in the K_s and $\theta(h)$ experiments. This was due to an immediate need for moisture retention and bulk density data whose tests require termination of the cores. The second set of cores were saved for miscible displacement experiments.

STATISTICS

Means and standard deviations were computed for each soil property for each sample volume and depth. Equality of variances between each size was determined using an F-test where the null hypothesis that all the variances are the same was rejected if

$$F_{max} = \frac{S^2_{max}}{S^2_{min}} > F_{crit} \qquad df=n-1,m \qquad [4]$$

where F_{max} is the ratio of the largest (S^2_{max}) to the smallest (S^2_{min}) error variances for m groups being compared and n is the number of observations in a group; F_{crit} is the appropriate ($\alpha = 0.05$ or 0.01) critical value in the F_{max} table with df as the smallest of the degrees of freedom for S^2_{min} and S^2_{max}. If variances were not different, then analysis of variance was performed using ANOVA for balanced data and general linear models (GLM) for cases with missing data points to obtain the mean square for error (MSE), the F-value (ratio of the mean square for the model divided by the MSE), and error degrees of freedom (Barr et al., 1976). These values were used in the Duncan's Multiple Range test to test the hypothesis that the group means for sample size were equal. The usual levels were tested (0.10, 0.05, 0.01). Note in the Bt horizon, the small cores were omitted for reasons detailed in the results section so a two variance F test was performed and means were compared using a standard t-test.

Hydraulic conductivity is generally observed to be log-normally distributed areally (McIntyre and Tanner, 1959; Nielsen et al., 1973; Baker and Bouma, 1976; Cameron, 1978). Measured saturated hydraulic conductivities were log-transformed and plotted on probability paper for each sample size at each depth (Figures 2 and 3). A least-squares regression equation was used to determine the correlation coefficient of each plot. High r^2 values (~ 0.95) confirm that K_s is log-normally distributed. Only one plot, for the medium cores in the Ap horizon did not normalize after the log-transformation (r^2 =0.65). This result does not necessarily vitiate the assumption of a lognormal population distribution since it is not certain whether 19 cores of this size are adequately representative. Correlation coefficients of fractile diagrams for all transport parameters for all cores are reported in Appendix O. Differences in position and slope of these cumulative frequency distributions illustrate differences in means and standard deviations between sample sizes and field measured K_s. Expected means $<\bar{X}>$ were calculated by

$$<\bar{X}> = \exp\,(\bar{X}_{ln} + \tfrac{1}{2}\, S_{ln}{}^2) \qquad [5]$$

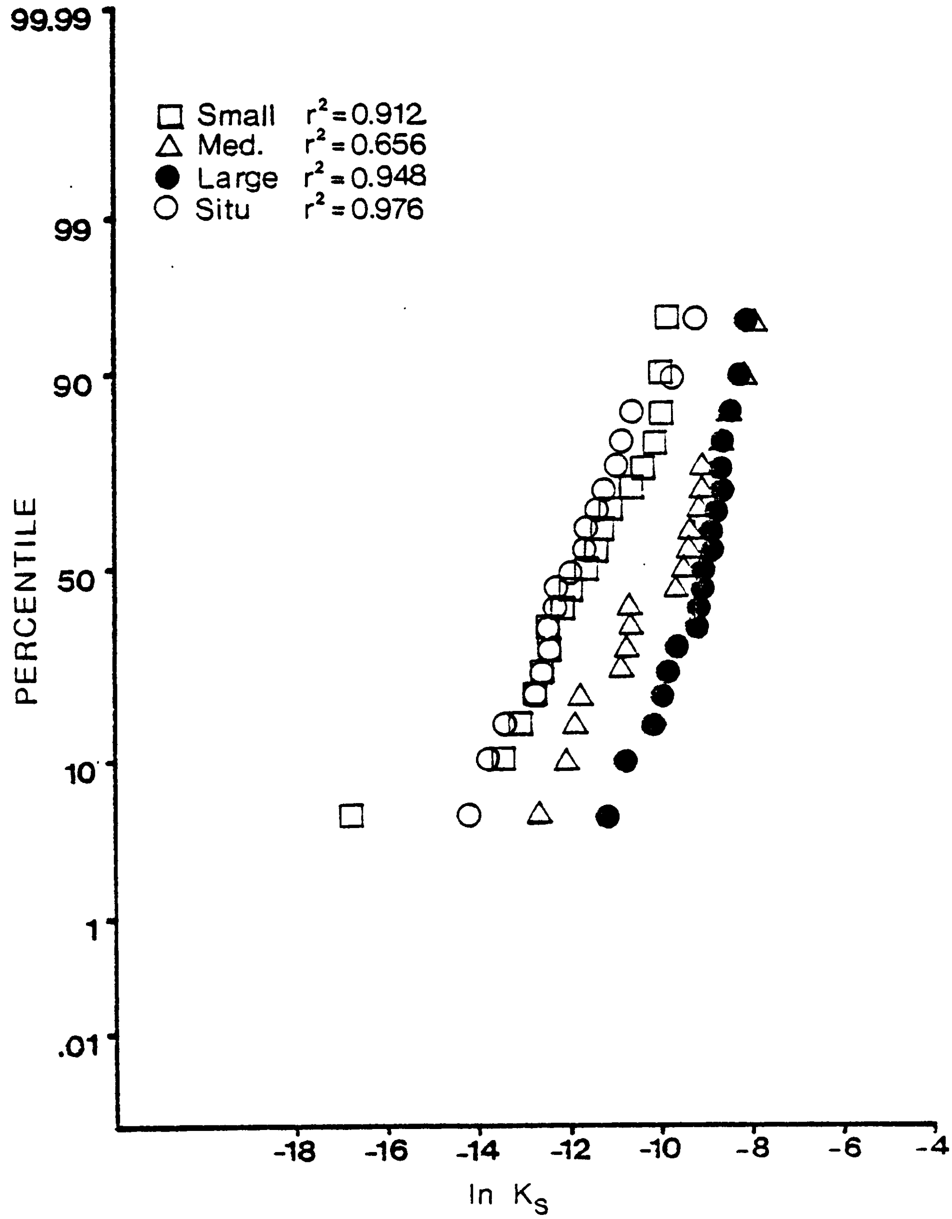

Figure 2: Cumulative frequency distribution for $\ln K_s$ Ap horizon, n=19.

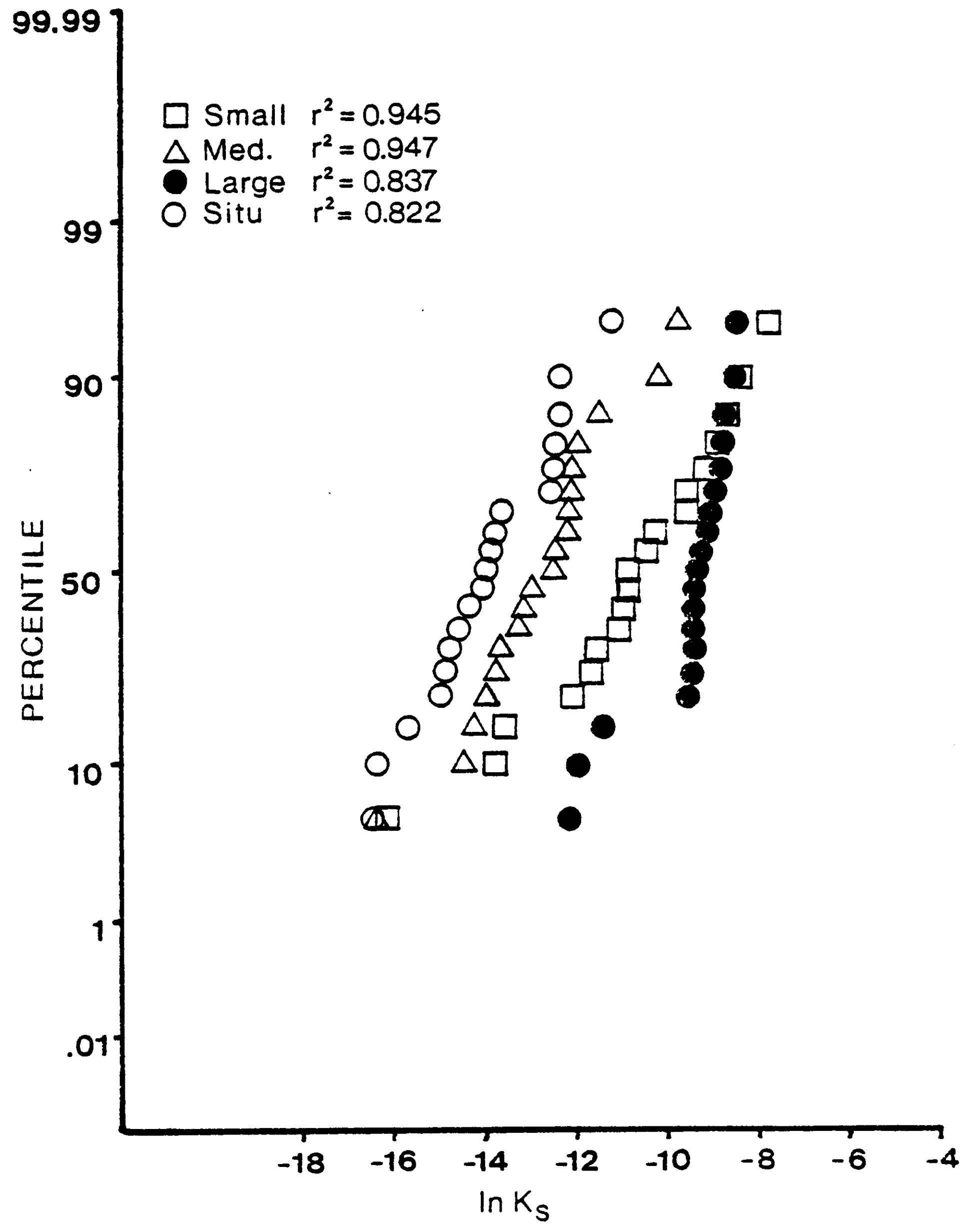

Figure 3: Cumulative frequency distribution for $\ln K_s$ Bt horizon, n=19.

where $\bar{X}_{ln}$ and S_{ln}^2 are the mean and variance of the log-transformed values. Variance and mean statistics were calculated using the log-transformed data.

Solute transport parameters have also been observed to be lognormally distributed (Simmons, 1982; Warrick and Nielsen, 1980; Biggar and Nielsen, 1976). Cumulative frequency distributions were plotted for logarithms of pore water velocities, dispersion coefficients and dispersivities for all core sizes in both horizons. Results for the small cores in the Ap horizon are shown (Figure 4). High r^2 values ~(0.9) support the assumption of lognormality. Variance and mean comparisons for these parameters were done using the log-transformed data.

Average solute breakthrough curves were calculated for each core size by

$$\bar{c}(T) = \sum_{i=1}^{n} c(T)_i v_i / \sum_{i=1}^{n} v_i \qquad [6]$$

where $\bar{c}(T)$ is the average concentration at a specified pore volume (T) and n is the number of cores. Observed pore volumes were determined as the cumulative volume of effluent divided by the total volume of fluid-filled pores. All breakthrough curves were normalized to a length of 0.1m by using model-calculated $c(T)_i$ with v_i and D_i values for each core. This procedure is in accord with suggestions by Park-

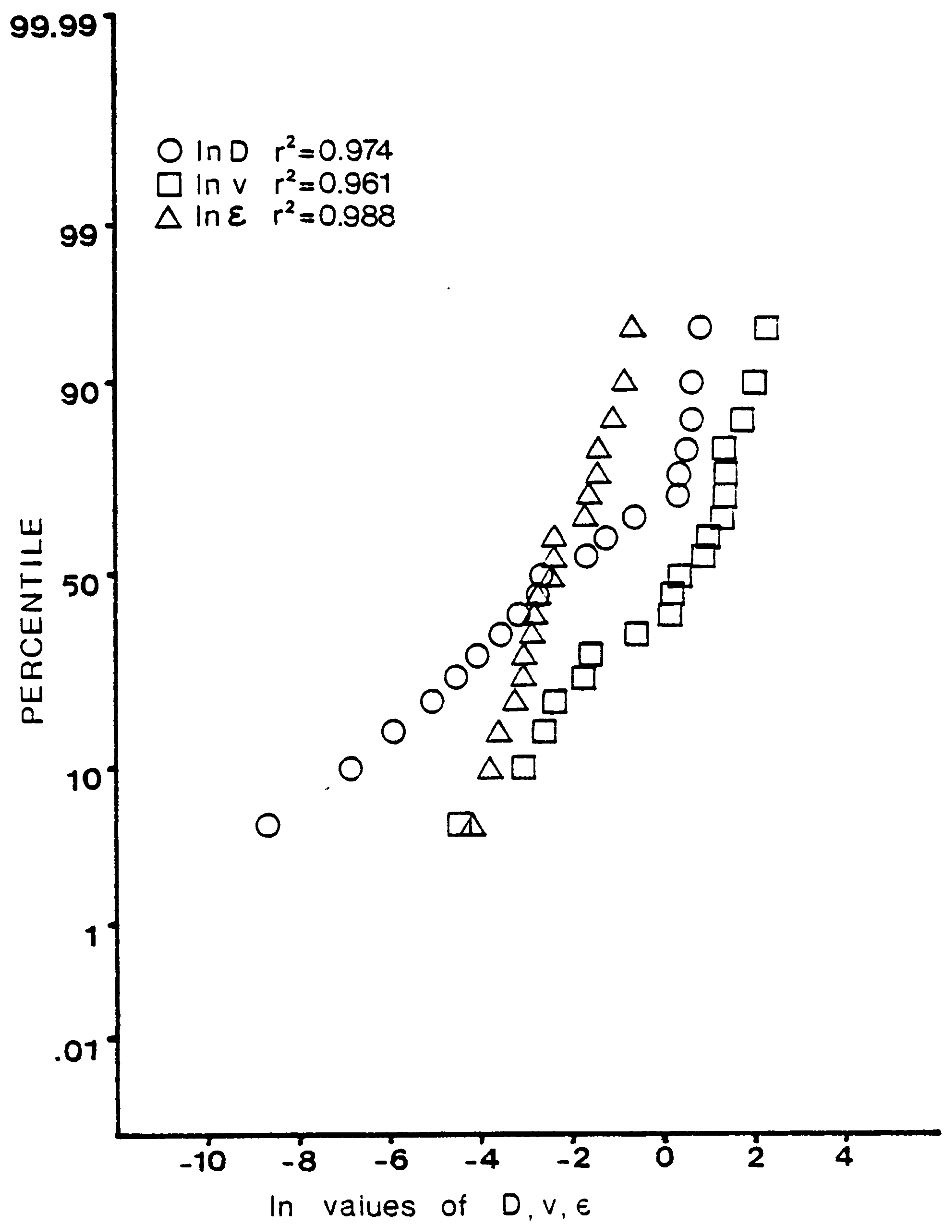

Figure 4: Cumulative frequency distribution for lnD, lnv, and lnε for small cores Ap horizon, n=19.

er and van Genuchten (1984) to obtain meaningful areally averaged flux concentrations.

Curves were first calculated for the experimentally determined transport parameters, then to predict average field BTC's and compensate for the low number of samples (n=19 for a given core size at each depth) a Monte Carlo method for multivariate normal distributions was employed. A modified version of the algorithm described by Rubinstein (1981) was used. Log-transformed pore water velocities and dispersion coefficients were generated as independent identically distributed IID N(0,1) random variables using the SAS (Barr et al., 1976) pseudorandom number generator for a normally distributed population with mean of zero and variance of one. Actual means of the 5000 random deviates for lnv and lnD were 0.004 and -0.007 with S^2 of 1.004 and 0.994, skewness was low (-0.023 and 0.014), and the Kolomogorov test showed no evidence to reject normality at the 0.01 level. Pore water velocities and dispersion coefficients were calculated from

$$v = \exp(\bar{X}_{lnv} + c_{11}*Z_{lnv}) \quad [7]$$

$$D = \exp(\bar{X}_{lnD} + c_{21}*Z_{lnv} + c_{22}*Z_{lnD}) \quad [8]$$

where $\bar{X}$ is the mean of the log-transformed values and Z is the random normal deviate for each variable

$$c_{11} = S_{\ln v} \qquad [9]$$

$$c_{21} = rf(S_{\ln v}^{-\frac{1}{2}} * S_{\ln D}^{-\frac{1}{2}}) \qquad [10]$$

$$c_{22} = (S_{\ln D}^{2} - c_{21}^{2})^{\frac{1}{2}} \qquad [11]$$

where r is the correlation coefficient of the linear regression of lnD versus lnv, S is the standard deviation of each variable, and f is an adjustable coefficient which was required to simulate the observed distributions of lnv and lnD (f values ranged between 1.0-1.2).
The pore volumes (T) used in these field predicted BTC's were obtained from T=vt/x where real time (t) was calculated using the expected mean pore water velocity as the first moment of the lognormal population distribution.

Short-range observation scale effects on variance were determined using an autocorrelation analysis described by Sisson and Wierenga (1981). Lateral variation in the log of fluid transport parameters was assumed to follow a first-order autoregressive process, i.e. the value at one position is inversely related to the value at the nearest neighboring position. Second-order stationarity is also assumed. The autocorrelation function for this process is defined as

$$\rho^{*} = \exp\left(-|u|\ \lambda^{-1}\right) \qquad [12]$$

where ρ^* is the mean autocorrelation between subsamples, u is distance, and λ is termed the integral scale of the process. To perform this analysis small cores were considered as subsamples taken inside the medium cores and medium cores were considered as subsamples taken inside the large cores. Because of this compositing it is expected that medium cores and large cores should be somewhat correlated to the small cores. This makes it necessary to determine ρ^* to estimate sampling variance. Autocorrelation coefficients were calculated from the observed variance ratios (S_L^2/S_S^2) and diameter ratios (d_L^2/d_S^2) of large to small samples by

$$\rho^*=(S_L^2/S_S^2-d_S^2/d_L^2)/(1-d_S^2/d_L^2) \qquad [13]$$

For the special case where samples are completely uncorrelated $\rho^*=0$ and this equation reduces to

$$S_L^2/S_S^2 = d_S^2/d_L^2 \qquad [14]$$

so the expected reduction in variance relative to the small cores with increasing distance is proportional to the ratio of sample areas. Integral scales were calculated from Eq.[12] using ρ^* from Eq. [13].

Field-scale spatial variability was analyzed using the semivariance method. This method was chosen over autocorrelation because the second-order stationarity constraint is not imposed. Semivariograms were computed from

$$\gamma(h) = [\, 1/\, 2N(h)\,] \sum_{i=1}^{N(h)} (x_i - x_{i+h})^2 \qquad [15]$$

where $\gamma(h)$ is the semivariance, h is the distance separation between data pairs, and N(h) is the number of data pairs separated by h (Journel and Huijbregts, 1978). To increase the number of data pairs at a particular h, semivariances for all h values falling within a certain range were combined so that γ and h represent averaged values. This yielded 6 data pairs for h=0.50 m, 12 for h=4.75 m, 38 for h=23.61 m, 10 for h=29.75 m, 39 for h=49.86 m, and 30 for h=74.82 m. Semivariograms are considered for only small distances in relation to the field (½ the transect length or 75 m in this case) in accord with a practical rule suggested by geostatisticians. Straight lines were visually fitted to the data. Ninety percent confidence limits about the $\gamma(h)$ were calculated using a Chi-square test (Burrough, 1983)

$$\frac{(N-h-1)\gamma(h)}{\chi^2_{0.05}} \leq \gamma(h) \leq \frac{(N-h-1)\gamma(h)}{\chi^2_{0.05}} \qquad [16]$$

where (N-h) is the number of data pairs and (N-h-1) is the degrees of freedom. The latter analysis assumes second-order stationarity.

RESULTS AND DISCUSSION

MACROPORE STUDY

Agreement between observed versus predicted breakthrough curves for monocontinuum and bicontinuum models is shown graphically for three cases (Figures 5-7). Figure 5 illustrates the worst fit of the monocontinuum model to experimental data out of the 114 samples. The mean error of reduced concentrations for the monocontinuum model is high (0.15). This is equivalent to an average fitting error of 1500/10,000 µM Br^- or 15%. An error this high suggests that the monocontinuum model is inadequate to describe solute transport through this large undisturbed ccre. Some improvement in fit may be obtained by omitting a few of the low T data points because of the fitting procedure used. The least-squares method preferentially fits the steepest portion of the curve since small changes in T give the largest changes in concentration and hence the largest squared residuals. BTC tails have much lower slopes and smaller residuals. The method minimizes the larger deviations in the initial portion of the curve and effectively neglects the tails--so the fitted curve shows good agreement in the initial portion while tail concentrations are consistently low. Omitting low T points would reduce this weighting effect and

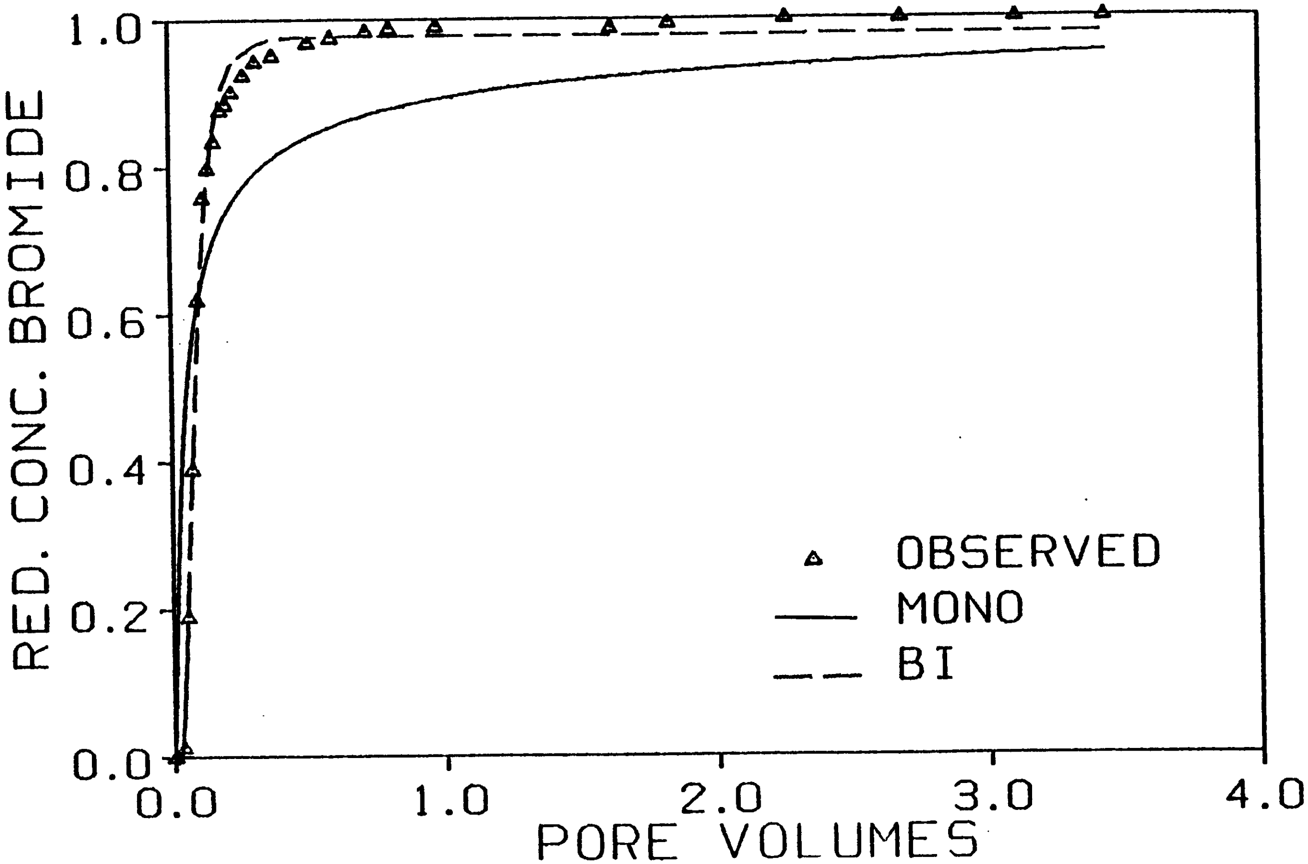

Figure 5: Comparison of BTC for observed, monocontinuum and bicontinuum models for the large surface core at subsite 2.

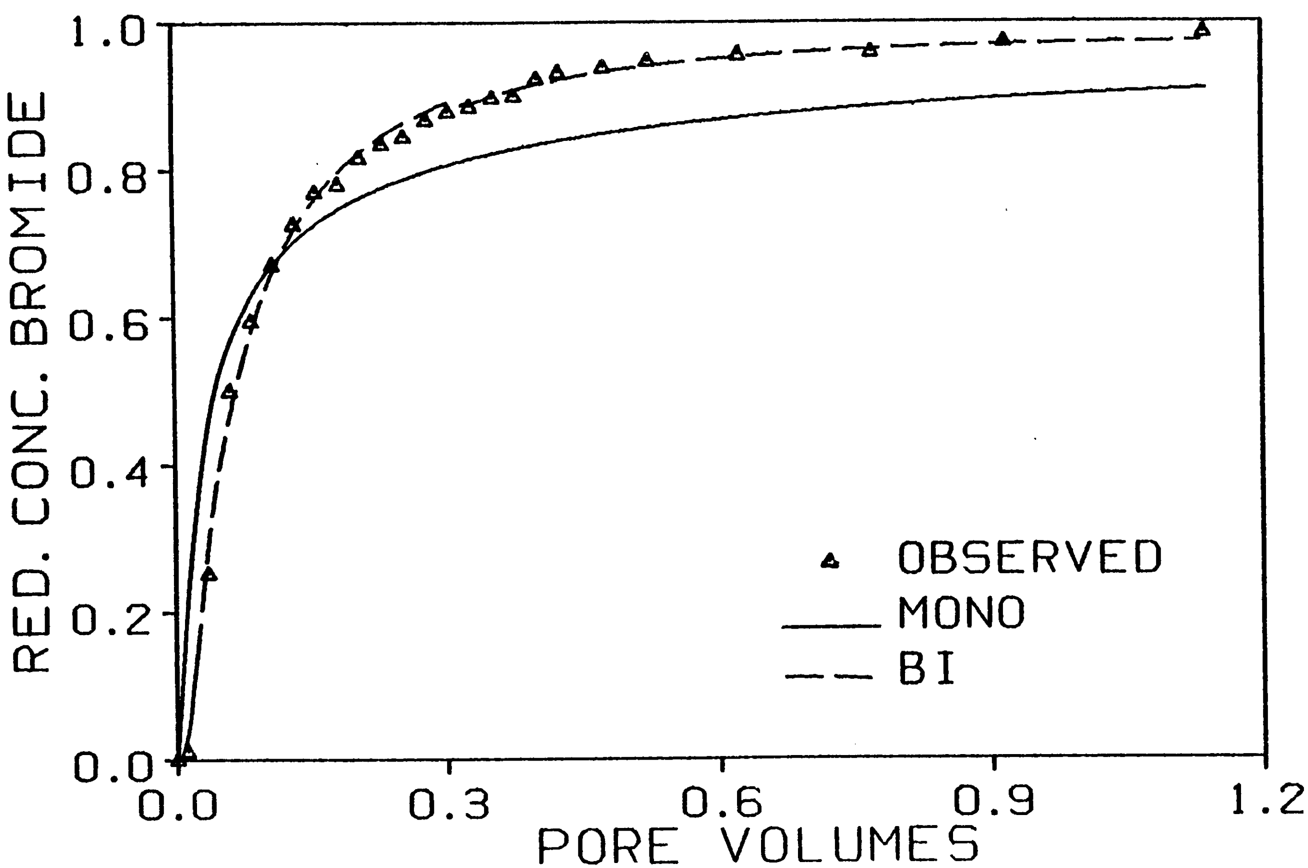

Figure 6: Comparison of BTC for observed, monocontinuum and bicontinuum models for the large surface core at subsite 7.

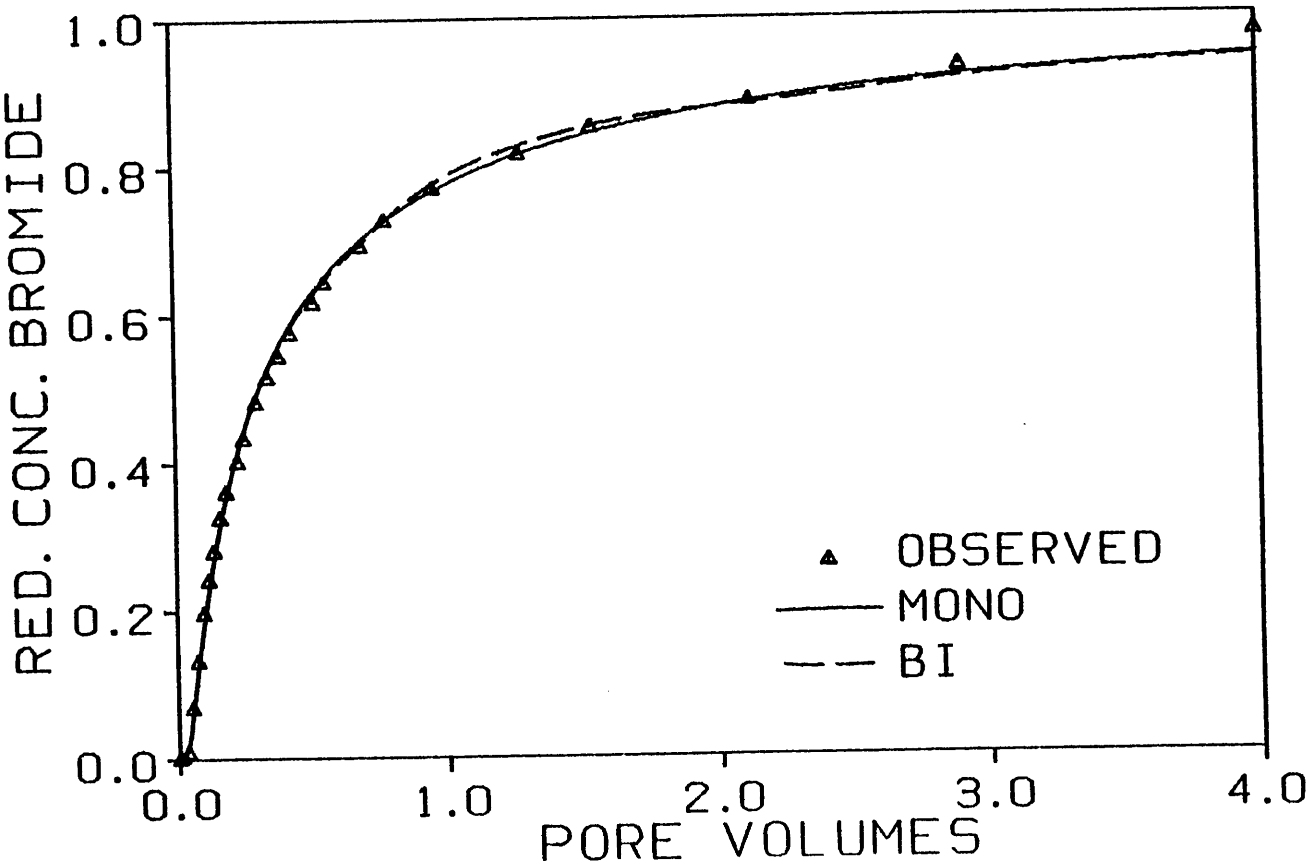

Figure 7: Comparison of BTC for observed, monocontinuum and bicontinuum models for the large surface core at subsite 13.

yield a slightly worse fit in the initial portion of the BTC and a better fit for tail values. However the model would still fail. Acceptable fitting errors for the purpose of predicting solute transport parameters may be be arbitrarily established. Errors of 5% or less might be desirable, but choosing one particular cut-off value is difficult. Two-region model results for the same core show a low mean error of 0.024 (240/10,000 µM Br^- or 2.4%) giving a very good fit to the data.

Figure 6 illustrates the second worst fit of the monocontinuum model to an observed BTC. The mean error for the monocontinuum model is still high (0.085). Several other cores have similar errors, the small A horizon core from subsite 6, the medium A horizon core from subsite 15, and the large B horizon core from subsite 9. These results cast serious doubts on the appropriateness of applying a monocontinuum approach to solute transport in soils containing macropores. One possible explanation for the poor monocontinuum fits may be that the cores are too short (giving low Peclet numbers). 'Long' cores increase the solute residence time in the soil and the likelihood of achieving monocontinuum between solute in mobile and immobile regions relative to the pore water velocity. Two-region model predictions agree very well with the observed data yielding a low mean error of 0.015.

Supporting arguments in favor of the monocontinuum model may also be made. Figure 7 shows the opposite extreme from the two previous figures. Both models predict the observed BTC very well with mean errors of 0.046 and 0.037 for the monocontinuum and bicontinuum models respectively. Before making decisions regarding appropriateness of these models it is necessary to quantify their mean errors for all samples (Tables 1 and 2). More than half of the monocontinuum predicted BTC's have mean errors of residual concentrations ≤0.05 and about 80% have mean errors ≤0.07. Comparatively, 90% of bicontinuum fitted curves have mean errors ≤0.05 and about 97% have mean errors ≤0.07. Significantly more curves are predicted with mean errors ≤0.05 for bicontinuum than monocontinuum models. However, broadening the error to ≤0.07 reduces this difference between models. Since a majority of the samples (80%) fall within the 0.07 error range for the monocontinuum model, this is probably the cut-off value which we need to feel comfortable with before declaring (in)appropriateness of the monocontinuum model. Although ≤0.05 may be a desirable error range, the choice is quite arbitrary depending on purpose and circumstances. Since our purpose is to estimate solute transport parameters and field-scale spatial variability is known to be high, 0.07 mean error is considered a satisfactory threshold value.

TABLE 1

Numbers of cores having mean errors at specified levels for the equilibrium model.

Core Size	Depth	n	>0.05	Mean Errors for Residuals >0.06	>0.07	>0.08	>0.09	>0.10
Small	Ap	19	7	6	4	3	1	0
Med	Ap	19	8	6	3	3	1	0
Large	Ap	19	8	8	5	4	3	3
Small	Bt	19	13	11	8	7	4	3
Med	Bt	19	10	8	5	0	0	0
Large	Bt	19	6	4	1	1	0	0
Total Cores			52	43	26	18	9	6
% of Total (n=114)			45.61	37.72	22.81	15.79	7.89	5.26

TABLE 2

Numbers of cores having mean errors at specified levels for the two-site model.

Core Size	Depth	n	Mean Errors for Residuals >0.05	>0.06	>0.07	>0.08	>0.09	>0.10
Small	Ap	18	1	1	1	1	0	0
Med	Ap	19	1	1	1	1	0	0
Large	Ap	19	3	1	1	1	1	0
Small	Bt	10	2	1	0	0	0	0
Med	Bt	0	-	-	-	-	-	-
Large	Bt	18	1	0	0	0	0	0
Total Cores			8	4	3	3	1	0
% of Total (n=84)			9.52	4.76	3.57	3.57	1.19	0.00

Many missing values are shown in the mean error tabulation for the bicontinuum model (Table 2). None of the medium Bt horizon data are reported. All but one of these cores had high r^2 values (most were ≥ 0.98, all others were ≥ 0.95, the lowest r^2 was 0.88) and low mean errors were ≤ 0.08 for the monocontinuum model. These data support the monocontinuum approach. These cores were not analyzed using the bicontinuum model since only slight improvements in fits would be expected and this would not necessarily aid in the choice of appropriate models. Nine small Bt horizon cores are missing from Table 2. Four of these had very erratic BTC data which was difficult to fit and no convergence was obtained. The other five missing cores were not run with the bicontinuum model after consideration of the unreliability of small cores in assessing solute behavior in the Bt horizon (this is discussed thoroughly in the section on sample volume effects). Note that omission of some of the more truculent BTC's may slightly bias the bicontinuum results. Poor fits for small Bt horizon cores were obtained with both models due to erratic data and do not discount the models' suitability.

Disadvantages associated with the two-site model must also be considered. Better fits are obtained using the bi versus the monocontinuum models, but this is because two additional parameters β and ω are being estimated. Physically β may be conceptualized as the fraction of mobile pores while ω is a first-order rate constant for mobile-immobile zone mass transfer. Model-fitted values for β however cannot be interpretted physically. Many β values approach 1.0 when it is expected that the mobile zone (i.e., macropores) is occupying only a small fraction of the total volume. Results by Parker and van Genuchten (1984b) show this discrepancy between physical interpretation of β and its estimated value. Estimated β in their wormhole study was 0.043, but calculations from known geometries showed an actual mobile fraction of 0.001. Part of this discrepancy may be ameliorated by using a model which considers diffusive control of mobile-immobile phase transfer instead of first order kinetics. Omega values are similarly of questionable physical significance. Some ridiculously high values are predicted, for example $\omega=2.25\times10^{6}$ with a standard error of estimation greater than 100% of the ω value for the small Ap horizon core at subsite 14, $\omega=1\times10^{6} \pm 7.5\times10^{6}$ for the large Ap horizon core at subsite 13, and ω approaching infinity with a matching standard error for the large Ap horizon core at subsite 14. One or both of the parameters β and ω will absorb some of the fitting error. Large standard errors suggest that little confidence can be placed in their values. Another problem is the difficulty encountered trying to get convergence of the solution. Initial guesses of D, β, and ω sometimes have to be repeated so many times that the initial guesses are almost equal to the estimated values. This procedure is tedious and expensive. It is more desirable to use a simpler model where appropriate.

Based on a mean error criteria of 0.07, we chose to estimate all solute transport coefficients using the monocontinuum model. This error is reasonable in light of the large field-scale spatial variability. Uncertainty in two additional fitted parameters which have no physical interpretation in the bicontinuum model is avoided. A monocontinuum approach is believed adequate for describing solute transport in these undisturbed soil cores containing macropores.

SAMPLE VOLUME STUDY

Bulk Densities and Moisture Retention Characteristics

Means and standard deviations for bulk densities (ρ_b) and moisture retention characteristics for small ($92cm^3$), medium ($471cm^3$) and large ($1767cm^3$) cores are reported for Ap and Bt horizons in Tables 3-5. Variances for each sample size for both properties in both horizons were found to be equivalent at all reasonable α levels (0.10, 0.05, 0.01) us-

Table 3 . ANOVA and mean bulk densities for small 92 cm^3, medium 471 cm^3 and 1767 cm^3 core volumes in the Ap and Bt horizons.

	bulk density ($Mg\ m^{-3}$)					
	Ap horizon			Bt horizon		
	Small	Med	Large	Small	Med	Large
$\bar{x}$	1.45^{ab}	1.47^{a}	1.38^{b}	1.41^{b}	1.58^{a}	1.51^{a}
S	0.13	0.10	0.13	0.14	0.12	0.13
n	19	19	19	19	19	19

^{a,b}Means with the same letter are not significantly different at the 0.05 level.

Table 4. Analysis of variance for water contents at specified matric tensions for Ap horizon. Field tension corresponds to θ at sampling.

Matric tension (m)	Small		Med		Large	
	$\bar{X}$	S	$\bar{X}$	S	$\bar{X}$	S
0.0	0.447^{a}	0.040	0.445^{a}	0.047	0.457^{a}	0.034
0.1	0.422^{a}	0.030	0.419^{a}	0.038	0.421^{a}	0.035
0.5	0.382^{b}	0.018	0.404^{a}	0.029	0.397^{ab}	0.032
1.0	0.360^{b}	0.017	0.369^{ab}	0.013	0.380^{a}	0.032
3.0	0.330^{b}	0.016	0.355^{a}	0.029	0.350^{a}	0.030
6.0	0.308^{b}	0.017	0.334^{a}	0.028	0.320^{ab}	0.029
10.0	0.289^{b}	0.018	0.317^{a}	0.028	0.294^{b}	0.026
Field	0.313^{b}	0.042	0.263^{c}	0.071	0.367^{a}	0.047

[a,b] Means in rows with the same letter are not significantly different at the 0.05 level.

Table 5. Analysis of variance for water contents at specified matric tensions for Bt horizon. Field tension corresponds to θ at sampling.

Matric tension (m)	Small		Med		Large	
	$\bar{X}$	S	$\bar{X}$	S	$\bar{X}$	S
0.0	0.412[a]	0.056	0.404[a]	0.051	0.408[a]	0.051
0.1	0.396[a]	0.042	0.386[a]	0.051	0.380[a]	0.054
0.5	0.384[a]	0.038	0.369[a]	0.056	0.361[a]	0.056
1.0	0.378[a]	0.039	0.361[a]	0.057	0.350[a]	0.057
3.0	0.367[a]	0.042	0.350[a]	0.058	0.332[a]	0.059
6.0	0.360[a]	0.044	0.338[ab]	0.057	0.318[b]	0.060
10.0	0.352[a]	0.049	0.326[ab]	0.058	0.304[b]	0.062
Field	0.336[a]	0.065	0.331[a]	0.052	0.333[a]	0.056

[a,b] Means in rows with the same letter are not significantly different at the 0.05 level.

ing an F-test. In the Ap horizon large cores had the highest θ_s (.46) while medium and small cores were slightly lower (0.45). Analysis of variance revealed that these values were not significantly different at the 0.05 level. Large cores had the lowest bulk densities (1.38 Mg m^{-3}) which were significantly lower than the medium cores at the 0.05 level, but not significantly different from the small cores. Since mean bulk densities for the small and medium cores were so close (1.45 and 1.47 Mg m^{-3}) it seems more reasonable to raise the criterion to the 0.01 level in which case the bulk densities for all sample sizes are not statistically different. Coefficients of variation for ρ_b and θ_s at both depths were low ranging from 7-12% (Table 6) in accord with other reported values (Warrick and Nielsen, 1980). Bulk densities generally are higher in the Bt horizon than the Ap as expected. Large and medium cores were not significantly different in the Bt horizon, but small cores had significantly lower bulk densities than the medium and large cores. This is probably due to fracturing in the small cores.

Moisture retention characteristics are similar for all sample sizes for Ap and Bt horizons; this is readily apparent in the average $\theta(h)$ curves (Figures 8 and 9). Because of the small variance in θ for all h in the Ap horizon (CV's all less than 10%) only slight differences in θ turn out to

Table 6 . Coefficients of variation (%) for selected soil properties for 3 sample sizes and in-situ for Ap and Bt horizons.

		Small	Med	Large	Situ
K_s	Ap	102.30	138.16	68.95	155.33
	Bt	134.42	165.28	58.40	147.02
V	Ap	107.42	80.20	160.41	
	Bt	226.88	137.51	94.21	
D	Ap	135.86	88.93	142.30	
	Bt	277.45	248.58	139.71	
ε	Ap	99.46	54.85	108.17	
	Bt	257.29	142.35	71.67	
bulk density	Ap	8.89	6.78	9.06	
	Bt	9.97	7.89	8.66	
θ (h=0)	Ap	8.85	10.61	7.44	
.1		7.06	9.16	8.43	
.5		4.73	7.24	8.09	
1.0		4.68	8.50	8.46	
3.0		4.91	8.11	8.60	
6.0		5.58	8.44	8.99	
10.0		6.11	8.91	8.95	
θ (h=0)	Bt	11.35	12.56	12.45	
.1		10.62	13.27	14.12	
.5		9.89	15.26	15.63	
1.0		10.39	15.81	16.38	
3.0		11.55	16.48	17.66	
6.0		12.34	16.94	18.93	
10.0		14.05	17.75	20.24	
θ (at sampling)	Ap	13.42	27.10	12.81	
	Bt	19.52	15.62	16.65	

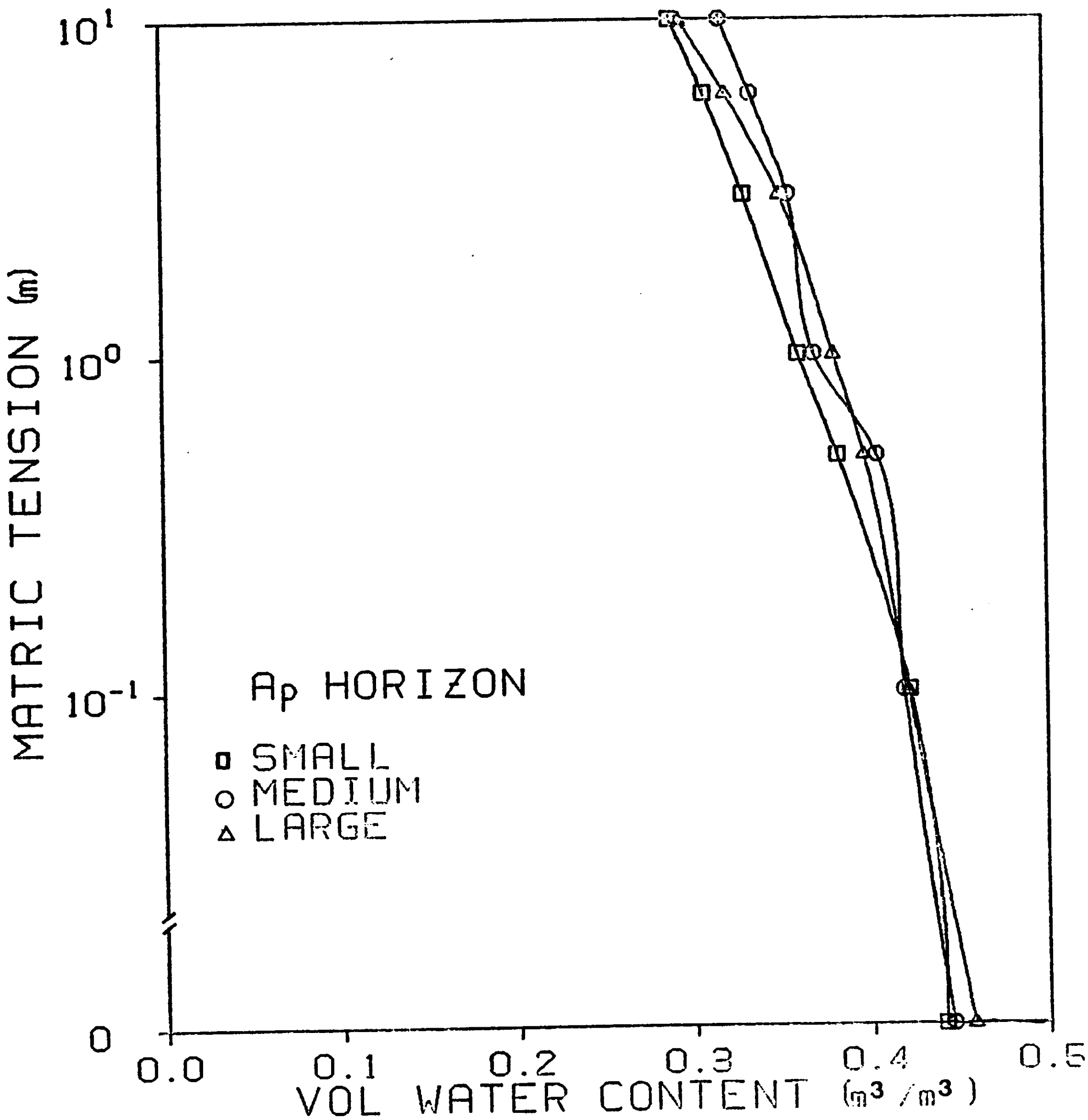

Figure 8: Moisture retention characteristics for the three core sizes in the Ap horizon.

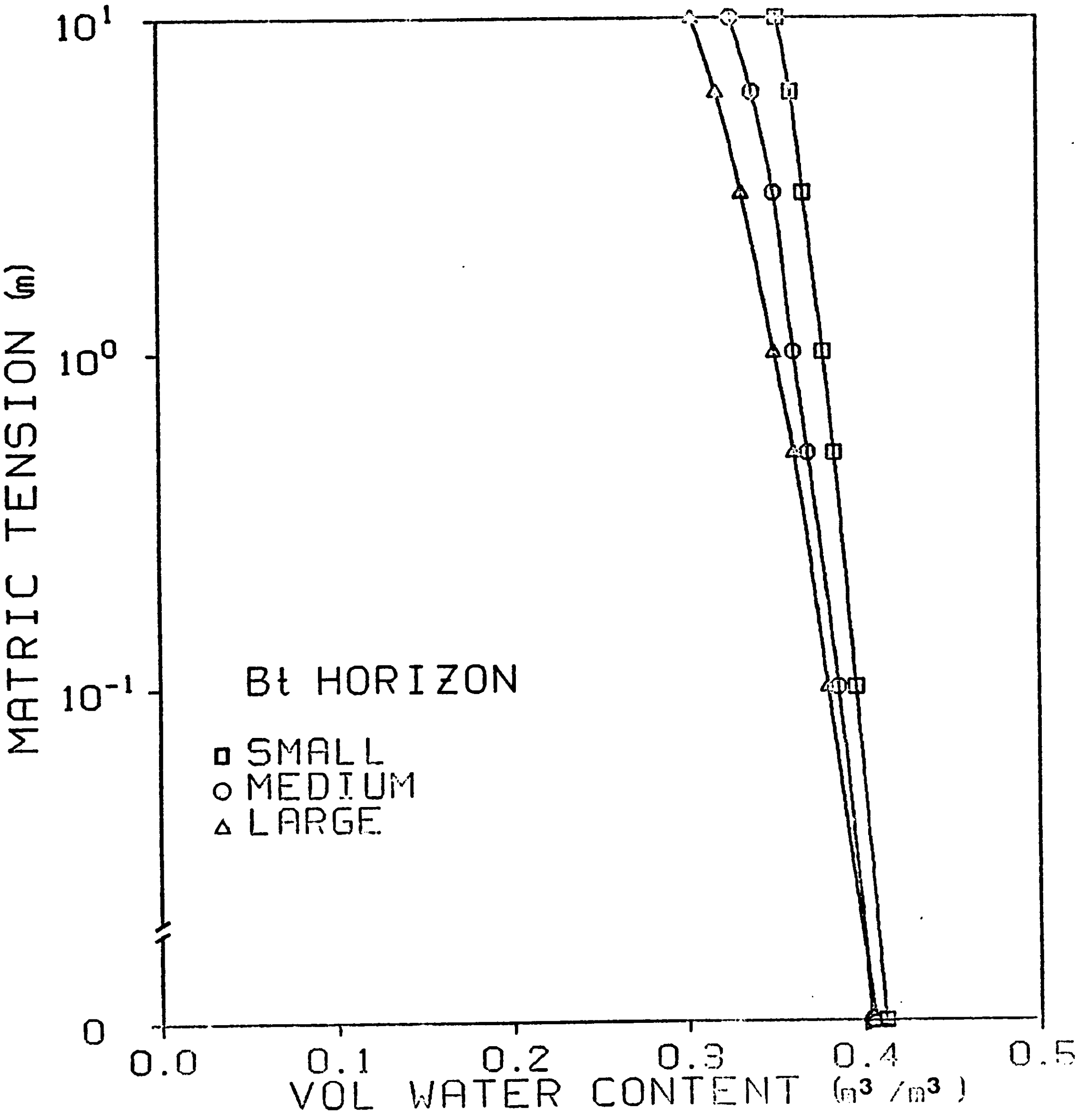

Figure 9: Moisture retention characteristics for the three core sizes in the Bt horizon.

be statistically significant (Table 4). At tensions greater than 0.1 m small cores have consistently lower moisture contents than the larger cores, but physically these differences are quite small (~0.02 m^3m^{-3}). In the Bt horizon, there seems to be a pattern of increasing divergence of θ with increasing tension where larger sample volumes yield lower θ for a given h. However, variance of θ in the Bt horizon is double that of the Ap with CV's ranging from 10-20%; this high variance makes detecting statistical differences more difficult (Table 5). Only at h=6.0 and 10.0 m do differences in θ's of 0.04 and 0.05 between sizes become significant. Comparing moisture desorption curves for the two depths, the rapid decreases in θ from ~0.45 to 0.30 in the Ap horizon versus the less dramatic change ~0.40 to 0.33 in the Bt horizon reflects the change in texture from silt loam to clay and the increased density of the Bt soil due to geostatic loads and illuviation. Moisture contents at sampling are also reported in Tables 4 and 5. Moisture retention and bulk densities for all cores are reported in Appendices A-F.

Results indicate that bulk density and $\theta(h)$ are not significantly influenced by sample volume. There were no significant differences in total porosity between the three sizes measured. Generally pore size distributions for the three sample volumes were similar; some divergence of moisture contents was observed in the Bt horizon, but high variances damped out the effects.

Saturated Hydraulic Conductivity

Expected mean values of K_s for the Ap horizon are relatively high ranging from about 1.4 to 8.4 m day^{-1} (Table 7). Coefficients of variation are also high ranging from 69% for the large cores in the laboratory to 155% for the field values; this is expected for lognormally distributed populations. It is important to note the trend of decreasing variance from 2.45 to 0.53 with increasing sample volume for small and large cores respectively. As previously mentioned, the S^2 ratio is inversely related to sample area via Eq.[12]. This relationship is shown in Figure 10 along with calculated variance ratios for small cores from A and B horizons. Variance does not drop as rapidly as would be expected if the samples were completely uncorrelated. This is due to the high autocorrelation even for the 150 mm diameter cores (Figure 11). From Eq.[13] the integral scale for the Ap horizon is 105 mm at which distance point-to-point correlation has only dropped by exp(-1) or 37%. This implies some short-range mutual dependence between the three sample volumes used. Physical significance of λ is that at a dis-

Table 7 . ANOVA and statistics for Ap horizon K_s (ms^{-1}). Expected mean $<\bar{X}>$ is exp ($\bar{X}_{ln}$ + 1/2 S_{ln}^2) where $\bar{X}_{ln}$ and S_{ln}^2 are the mean and variance of the ln-transformed values. Variance S^2 is for nontransformed values. Means with the same letter are not significantly different at the 0.01 level.

	SAMPLE VOLUME			
	Small	Med	Large	In-Situ
$<\bar{X}>$	1.63×10^{-5}	9.70×10^{-5}	6.57×10^{-5}	1.64×10^{-5}
S^2	1.05×10^{-10}	1.02×10^{-8}	1.92×10^{-9}	5.95×10^{-10}
$\bar{X}_{ln}$	-12.25^b	-10.48^a	-9.90^a	-11.86^b
S^2_{ln}	2.45	2.48	0.53	1.69
n	19	19	19	19

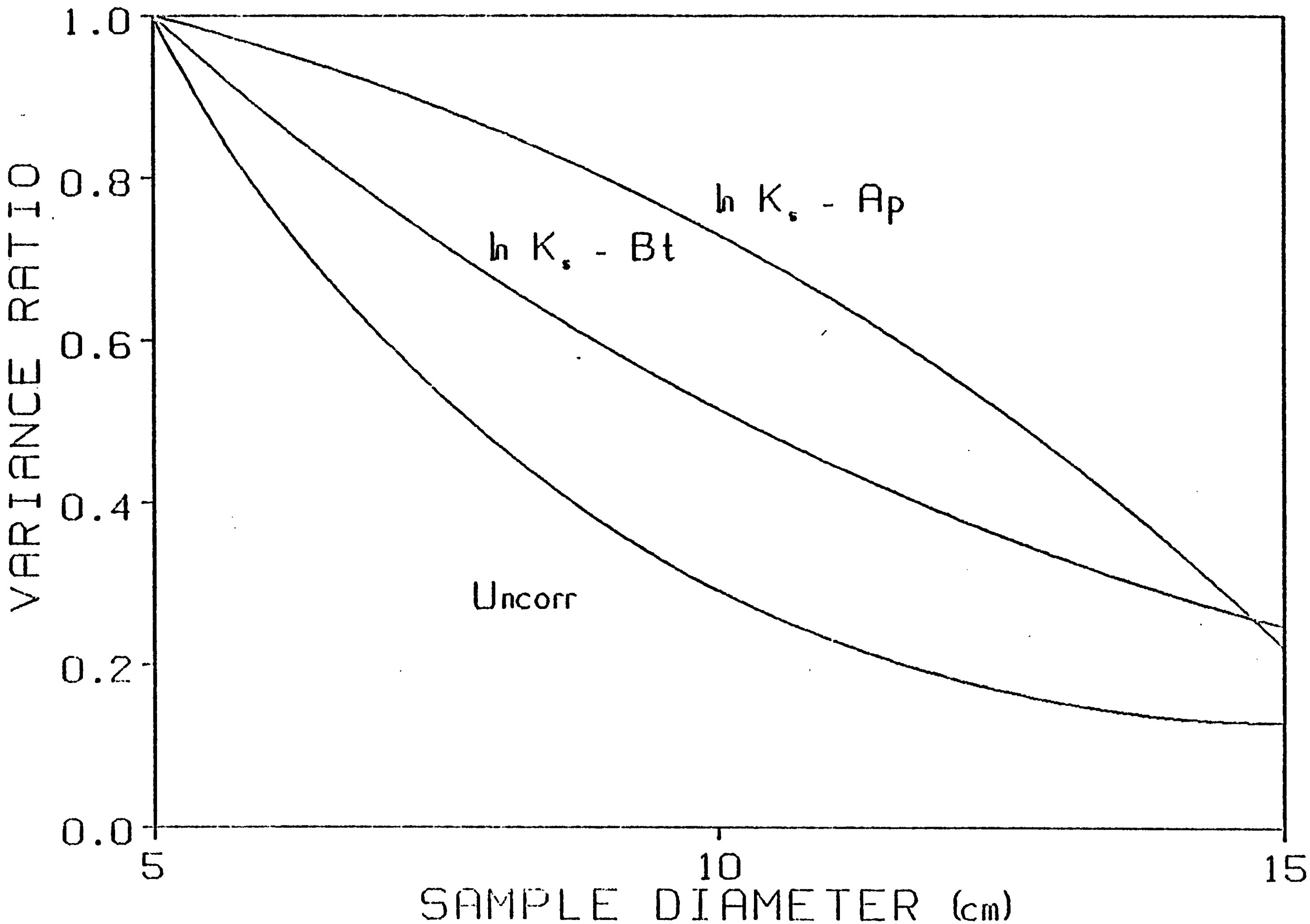

Figure 10: Reduction of variance of lnK s with increasing sample diameter for A and B horizons.

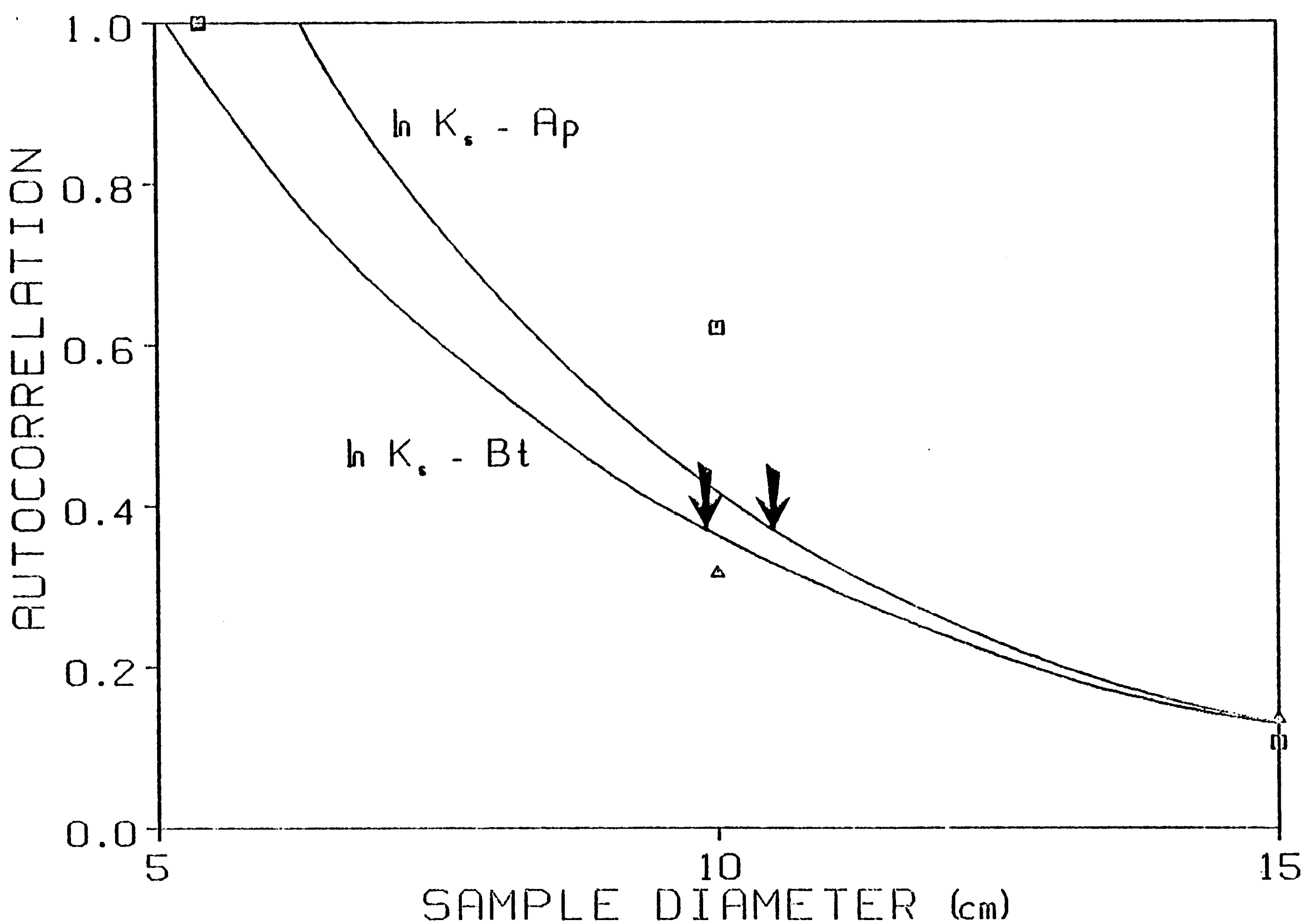

Figure 11: Autocorrelation of lnK s for A and B horizons. Arrows denote integral scales.

tance several times λ correlation is negligible. Interpretation of λ is restricted to this scale of observation. These results are in accord with Sisson and Wierenga (1981).

An F-test of equality of variances indicated significant differences at the 0.05 level. Large cores have significantly lower variance than the smaller samples since they incorporate more of the field heterogeneity. Since the variances are different, it is not valid to compare means using parametric statistics. However, much information is lost when real measured values are replaced by ordinal numbers therefore nonparametric methods are not pursued. Following the advice of Hawley et al. (1982) we chose to raise the criterion α to a more 'rational' value of 0.01. At this level variances are not significantly different so analysis of variance becomes legitimate for testing means.

Large and medium core K_s means are very similar in the Ap horizon, but the small core and in-situ K_s means are 4 times less and this difference is significant at the 0.01 level. It would be desirable if all sample volumes yielded the same mean K_s. Then larger samples having progressively less variance would require fewer observations to obtain the same level of accuracy and core volume would only be important in determining the number of cores to be taken. But it appears that in this case small cores probably suffered substantially more disturbance during the sampling procedure than the larger cores. Small cores had a disturbance index (ratio of core wall thickness to diameter) more than three times greater than that for the large cores.

Surprisingly the K_s measured in-situ is 4-6 times lower than lab-measured K_s from the large and medium core values. It was anticipated that field-measured values might be higher than lab-measured values owing to reduced disturbance of natural structure for the former. Field et al. (1984) reported in-situ K_s 6-20 times greater than laboratory values from undisturbed 54 mm diameter x 30 mm long cores for A and B horizons. Conflicting results are reported by Watts et al. (1982); they suspected that poor performance of drainage and irrigation systems in Florida was due to overestimates of K_s associated with a labortory procedure. A comparison of the laboratory method with an in-situ piezometer method revealed lab-measured K_s on 25 mm diameter x 100 mm long cores were 2-3 orders of magnitude higher than field-measured values for spodic and argillic horizons. No explanations were attempted. They concluded that the core method yields erroneously inflated K_s. Unfortunately they did not determine the accuracy of the piezometer method. It seems as likely that in-situ K_s values may be too low due to smearing at the bottom of the piezometer hole from augering since there was no mention of any precautions taken. Since core K_s was known to be too high perhaps the sampling technique induced shattering or side-wall channeling. Higher confidence is placed in the results by Field et al. (1984). Their in-situ test really was undisturbed since 3x3 m plots were used.

Several factors may be responsible for the incongruity of low in-situ K_s observed in our study. These factors reflect the inherent difficulty of obtaining accurate measurements in the field. Vegetation was removed so this may have caused crusting during the infiltration tests. Some of the tests ran for two hours before reaching an apparent steady-state so it is possible that we were measuring the resistance of some impermeable lower layer. Air may have been entrapped in aggregates during wetting. Ensuring proper seals on tensiometers was a problem. Differences in means and variances can also be seen in the displacement of the small and field fractile diagrams to the left of the large and medium ones.

Since small cores yielded a similar K_s mean to the in-situ K_s mean, an argument supporting them as adequate to estimate K_s might be tempting at first glance. Differences in sampling procedures (small cores were taken using a hydraulic sampler and medium and large cores were taken by carefully driving rings in by hand) might be cited as reasons for different K_s values, however by observation it was determined that no core-wall channeling was occurring at least in the large cores. So most confidence is placed in the large core data.

Expected mean values of K_s for the Bt horizon are generally lower than the Ap horizon since clay content increases, but exhibit a wider range from about 0.2 to 6.0 m day^{-1} and higher variation with CV's ranging from 58% for the large cores to about 150% for the other cores and field K_s (Table 8). The same pattern of decreasing variance with increasing sample volume is observed even more dramatically in the Bt horizon than the Ap horizon; small cores had the highest variance of 4.21, medium cores had half as much, and large cores had one-fourth as much. Reduction of S^2 relative to the small cores with increasing diameter again is not as rapid as if the cores were completely uncorrelated suggesting some short-range dependence (Figure 10). Exponential decay of autocorrelation in the Bt horizon occurs over shorter distances than for the Ap $\ln K_s$; the shorter integral scale of 99 mm reflects this (Figure 11). Differences in variances were significant at the 0.05 level. Using the same reasoning as for K_s in the Ap, means are compared. In this case, the large and small cores yield similar means (only about 1.2 times different) while large cores have a

Table 8. ANOVA and statistics for Bt horizon K_s (ms^{-1}). Expected mean $<\bar{X}>$ is exp ($\bar{X}_{ln}$ + 1/2 S_{ln}^2) where $\bar{X}_{ln}$ and S_{ln}^2 are the mean and variance of the ln-transformed values. Variance S^2 is for nontransformed values. Means with the same letter are not significantly different at the 0.01 level.

	SAMPLE VOLUME			
	Small	Med	Large	In-Situ
$<\bar{X}>$	6.91×10^{-5}	3.95×10^{-6}	5.80×10^{-5}	2.44×10^{-6}
S^2	1.54×10^{-9}	3.54×10^{-11}	7.79×10^{-10}	9.24×10^{-12}
$\bar{X}_{ln}$	-11.69^{b}	-13.43^{c}	-10.24^{a}	-13.97^{b}
S^2_{ln}	4.21	1.97	0.98	2.09
n	19	19	19	19

much lower variance. Medium cores had significantly lower mean K_s probably due to clogged pores from bacterial growth during an extended saturated period at room temperature. Again the low in-situ K_s are dubious. Saturated hydraulic conductivities for all cores are reported in Appendices G and H.

Solute Transport Parameters

Expected mean values of dispersion coefficients (D) are almost 100 m^2 day^{-1} for the Ap large core samples with coefficients of variation approaching 150% (Table 9). Differences between core sizes for variances of log-transformed data are not significantly different at any reasonable level (0.10, 0.05, 0.01) for any of the solute parameters. Mean D values for large and medium cores are similar, but both are significantly higher than the small core means at the 0.05 level. This may be partially explained by the pore water velocities (v) which are three times greater in the large cores than the small cores (which is about the same ratio as large core K_s to small cores K_s). Generally, dispersion coefficients increase proportionally with the pore water velocity (Nielsen and Biggar, 1982). Differences in the mean v may be due to differences in what Bouma (1982) calls "pore continuity patterns". He suggests that pore size may

Table 9. ANOVA and statistics for Ap horizon solute transport parameters. Expected mean is the first moment of the log PDF. Variance (S^2) is for nontransformed data. Means with the same letter are not significantly different at the 0.05 level. Dispersion coefficients are estimated from an equilibrium model.

	Ap Horizon - Solute Transport Parameters								
	v (m day^{-1})			D (m^2 day^{-1})			$\varepsilon = Dv^{-1}$ (m)		
	Small	Med	Large	Small	Med	Large	Small	Med	Large
$<\bar{X}>$	6.21	15.12	17.82	4.12	24.33	92.85	0.15	0.59	1.60
S^2	7.82	35.11	537.06	0.60	16.95	1121.31	0.020	0.085	2.58
$\bar{X}_{ln}$	-0.13^b	1.38^a	1.67^a	-2.57^b	0.51^a	1.56^a	-2.44^c	-0.87^b	-0.11^a
S_{ln}^2	3.91	2.67	2.43	7.97	5.36	5.94	1.06	0.68	1.15
n	19	19	19	19	19	19	19	19	19

not be as important as continuity since small continuous pores may transmit more fluid than large dead-end pores. Large sample volumes appear to contain more continuous pores due to truncation of pores by walls in small cores. Higher dispersion coefficients for large cores are probably more reflective of the actual field situation (Schwartz, 1977; Bresler and Dagan, 1979).

Dispersivities (ε) reveal some interesting information. If v and D are highly correlated then the coefficients of variation for ε should decrease substantially possibly even approach zero. However large core D values have a CV of 142% which only drops to 108% for ε and the other sample sizes show the same trend (Table 9). This indicates that v is not solely responsible for variation in D; complicated pore geometries with much tortuosity and inter-connectedness must be a characteristic of this soil. Solute transport parameters for all Ap horizon cores are reported in Appendices I-K.

Breakthrough curves (BTC) are useful to characterize flow patterns in soil. Qualitative interpretations can be made in terms of assumed flow through 'large' and 'fine' pores depending on how rapidly the solute elutes and the shape of the curve. Average BTC's are compared for each core size in the Ap horizon (Figure 12). All curves show

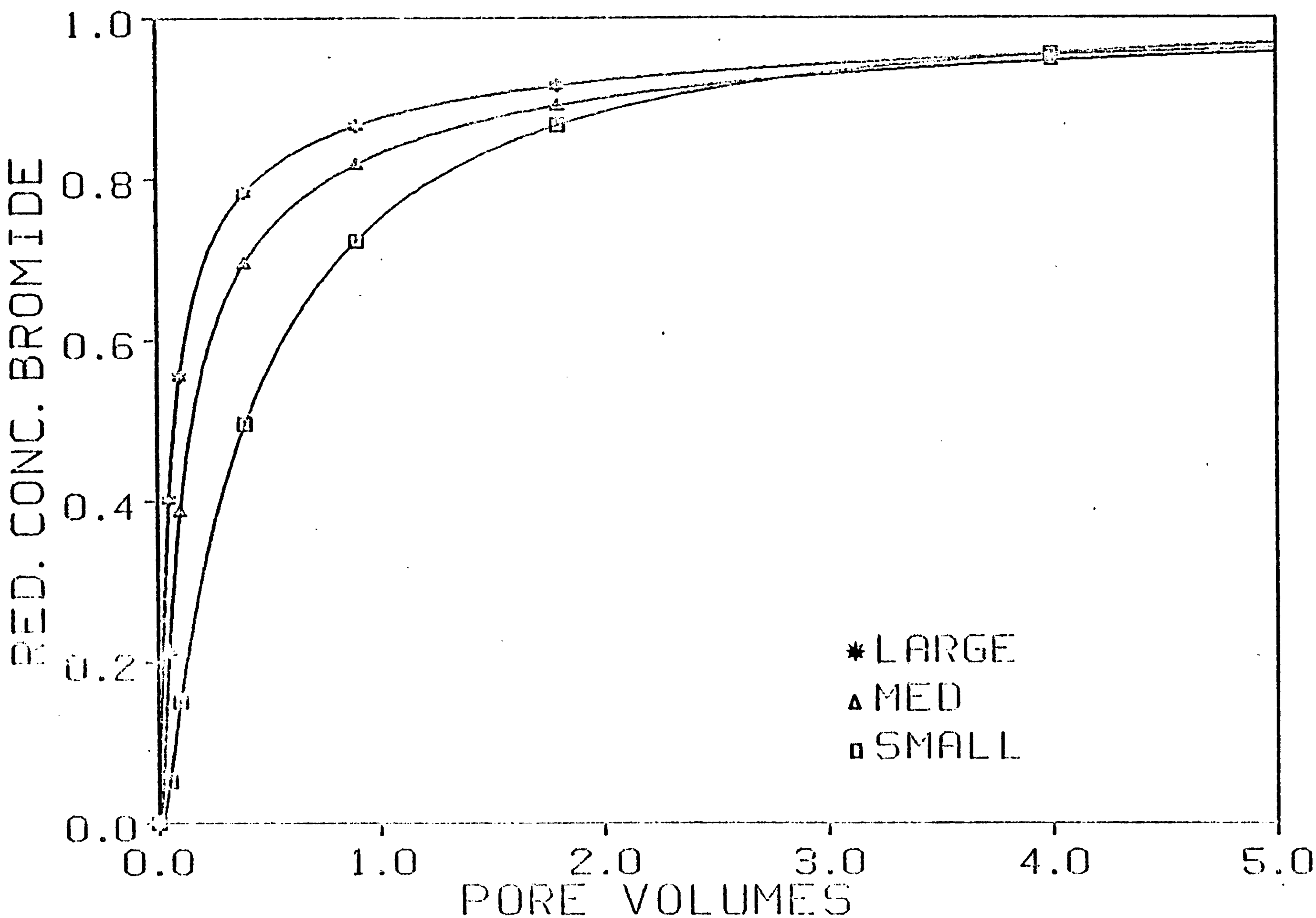

Figure 12: Average breakthrough curves for surface horizon for all core sizes using n=19.

rapid breakthrough of solute and extended tailing with effluent concentrations gradually reaching a reduced concentration of 1.0. These phenomena indicate the presence of large continuous pores since the incoming solution must bypass much of the resident liquid. In the Ap horizon these are most likely biological in origin owing to plant roots, worm activity and other soil fauna. Such biopores by virtue of their formation tend to be continuous (Clothier and White, 1982). There is a definite trend towards higher reduced concentrations at any given pore volume (T) for larger cores with initial bromide breakthrough for large and medium cores occuring much more rapidly than for small cores. At T = 0.05, the reduced concentration for large cores is already 0.40, for medium cores is 0.22 and for small cores is only 0.05; by T = 0.50, reduced concentration of bromide is up to 0.81 for large cores, 0.73 for medium cores and 0.56 for small cores. These BTC agree with other published data. Bouma et al. (1976) reported that chloride transport occurred mainly through a few relatively large continuous pores in saturated cores of Dutch 'knik' clay soils such that the tracer species appeared in the eluent after only a thousandth of a pore volume. Theoretical studies by Scotter (1978) and supporting lab and field experimental data by Kanchanasut et al. (1978) predict BTC's exhibiting reduced concentrations of 0.8 after T=0.01 for soil with 0.4 mm diameter continuous vertical channels; they also found significant amounts of tracer in the eluent in less than a minute or less than T=0.05 for an undisturbed core containing a 3 mm diameter wormhole ($K=2.3\ m\ d^{-1}$). Bouma and Wosten (1979) found that only a few larger pores occupying a small volume could determine the shape of the BTC and they advocated the use of large cores to adequately represent these larger pores. This seems to be the case here also. Large cores in this study appeared to have very large wormholes with sizes typically ranging from about 3-5 mm, but sometimes up to 8 mm. So the observed rapid breakthrough is not surprising. Faster breakthrough of solute in the larger cores suggests either a greater fraction of macropores and/ or more continuous pores in the large samples. The probability of sampling large wormholes in the small cores is much less than the large cores.

Expected mean values of D for the Bt horizon are orders of magnitude smaller than the ones for the Ap horizon ranging from about 0.01 for small cores up to 3 $m^2\ day^{-1}$ for large cores with much higher variation - CV's ranging from about 275% for small cores to 140% for large cores (Table 10). Lower dispersion coefficients are attributable to lower pore water velocities. Much difficulty was encountered

Table 10. ANOVA and statistics for Bt horizon solute transport parameters. Expected mean is the first moment of the log PDF. Variance (S^2) is for nontransformed data. Means with the same letter are not significantly different at the 0.01 level. Dispersion coefficients are estimated from an equilibrium model. Small cores are omitted from statistical comparison.

	Bt Horizon - Solute Transport Parameters								
	v ($m day^{-1}$)			D ($m^2 day^{-1}$)			$\varepsilon = Dv^{-1}$ (m)		
	Small	Med	Large	Small	Med	Large	Small	Med	Large
$<\bar{X}>$	0.048	2.34	3.34	0.0070	1.61	2.89	1.15	0.20	0.42
S^2	0.0072	6.51	4.86	0.00048	3.79	2.60	2.70	0.078	0.075
$\bar{X}_{ln}$	-5.28	-1.24^{b}	0.24^{a}	-7.32	-3.59^{b}	-1.04^{a}	-2.04	-2.35^{b}	-1.27^{a}
S^2_{ln}	4.48	4.18	1.94	4.72	8.12	4.20	4.36	1.47	0.83
n	19	19	19	19	19	19	19	19	19

running the miscible displacement tests on the small cores. Fluxes were so slow for many samples that inflow heads had to be increased to yield about 1.5 times the gradients of the other samples just to obtain a flux yielding about one pore volume in a month. Erratic breakthrough curves showing some drops in effluent concentration over time as opposed to monotonically increasing concentration were observed for many small cores. This may have been due to concentration/ dilution effects caused by evaporation and residual liquid in flasks after aliquot sampling. Two extreme cases reached reduced concentrations of about 1.0 in only T=0.20; for these cases solute must have been transported predominately by diffusion since the volume of effluent was small over a long time. Standard errors on estimated D values from small core data were typically 20-30%, but one was as high as 72% so little confidence can be placed in these values. Resulting dispersivities for small cores were anomalously high, for example 2.5, 3.3, and 11.6 m. This is unexpected due to the extremely low v values. Consequently, the mean ε was probably erroneously inflated. For these reasons small cores were omitted from statistical comparisons.

Large cores have significantly higher pore water velocities, dispersion coefficients and dispersivities than medium cores with much lower variation. Interestingly when large BTC's are averaged by weighting concentrations with pore water velocities and medium BTC's are averaged in the same manner, the plots are virtually identical (Figure 13). Both core volumes contain wide pore size ranges. Just a few fast pore water velocities are enough to dominate the transport process. In this case there does not appear to be any advantage to using large cores over medium cores except that due to their lower variance fewer large samples would be needed to obtain the same level of accuracy. However larger cores may also be harder to handle. Reduction of variance of $\ln\varepsilon$ relative to the small cores with increasing diameter in the Bt horizon is very rapid; it closely follows the prediction for completely uncorrelated samples (Figure 14). Very low autocorrelation coefficients are seen for medium and large cores (0.07 and 0.06, respectively) and the integral scale of 72 mm is relatively short(Figure 15). This implies a low spatial correlation at this scale. Solute transport parameters for all Bt horizon cores are reported in Appendices L-N.

Solute behavior in the Ap and Bt horizons is compared for large cores (Figure 16). Both horizons exhibit rapid breakthrough behavior reflective of wide pore size distributions with continuous large pores, but the Ap horizon elutes Br^- much faster; at T=0.1, the mean reduced concentration is

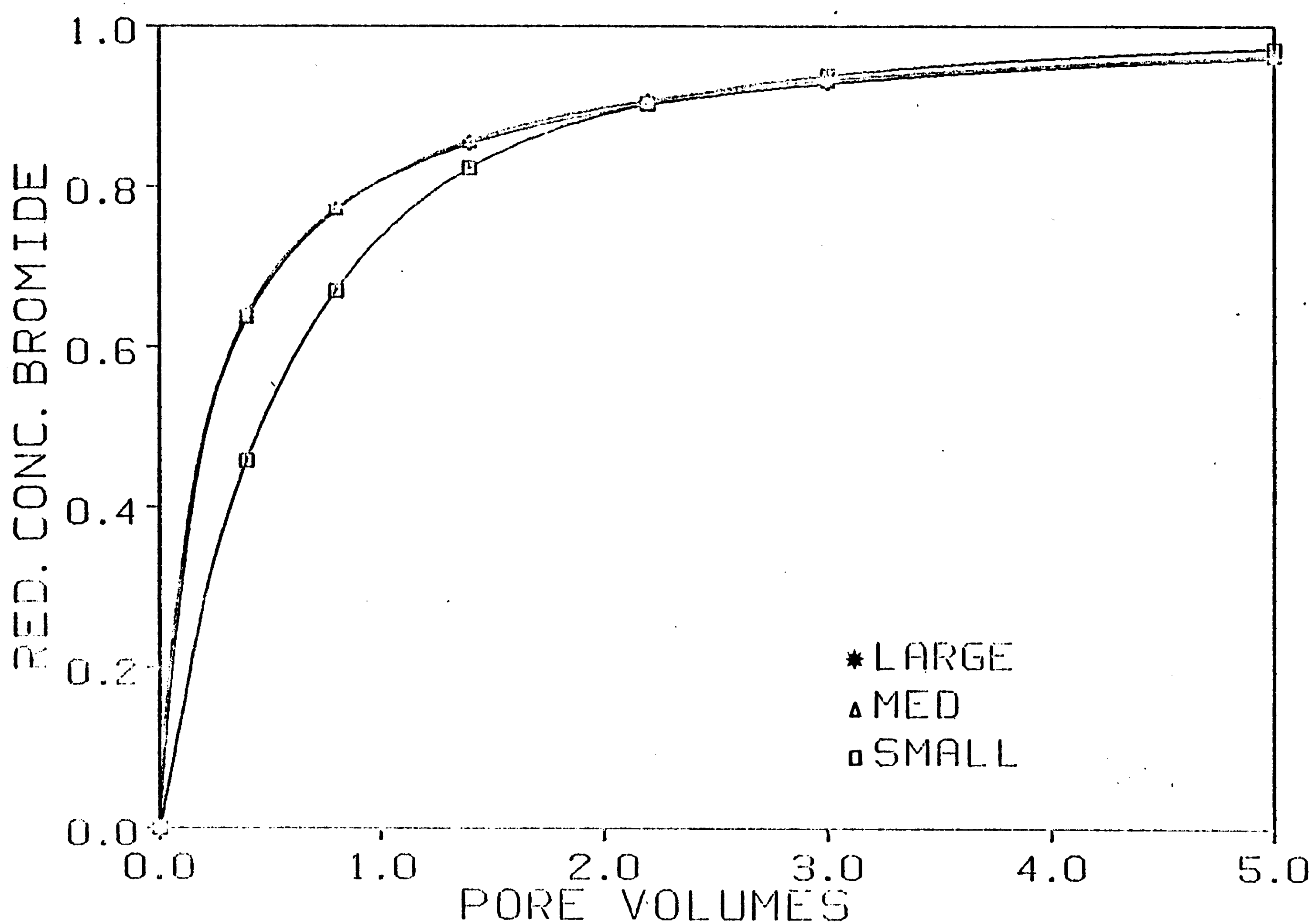

Figure 13: Average breakthrough curves for subsurface horizon for all core sizes using n=19.

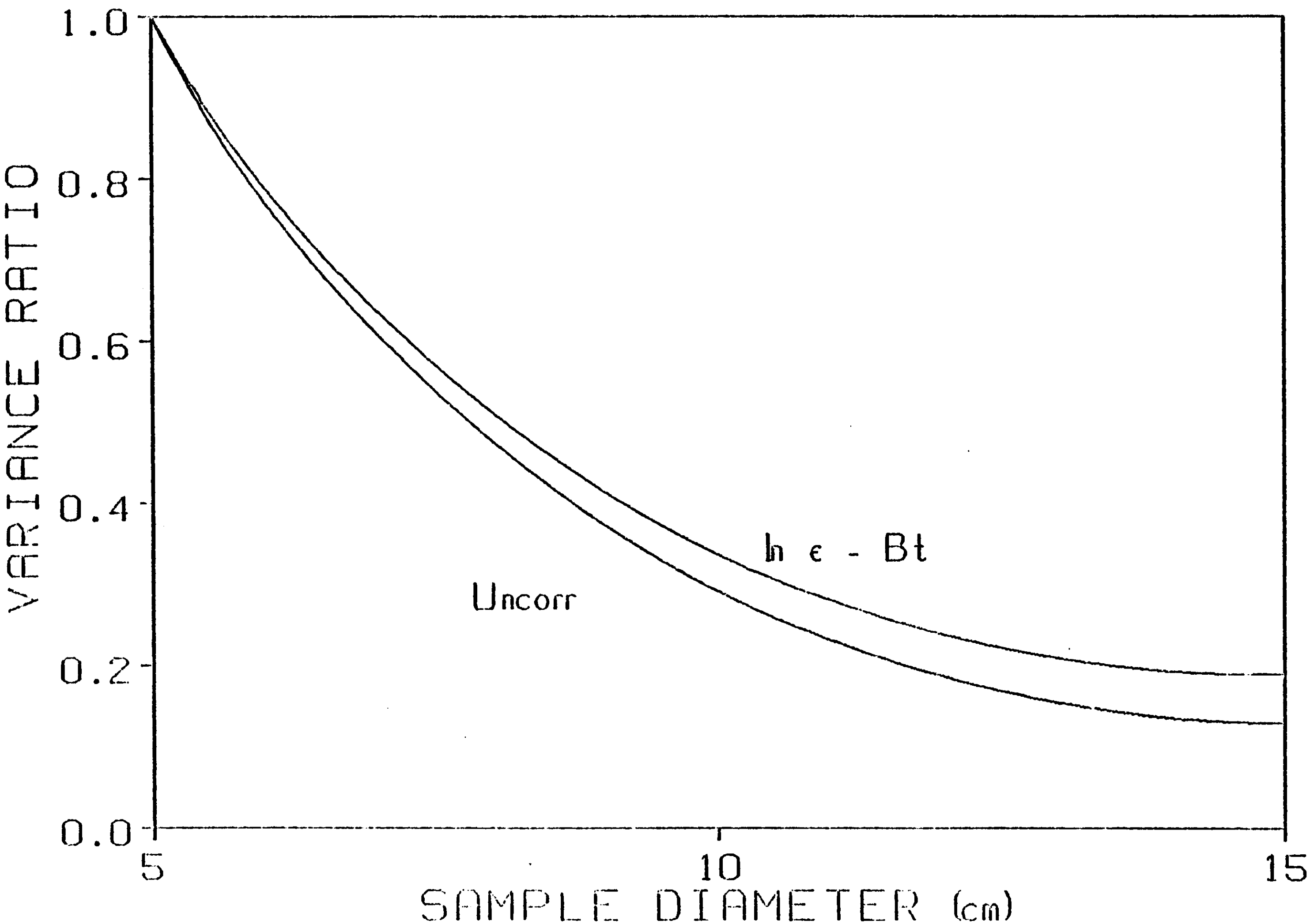

Figure 14: Reduction of variance of $\ln\epsilon$ with increasing sample diameter for the B horizon.

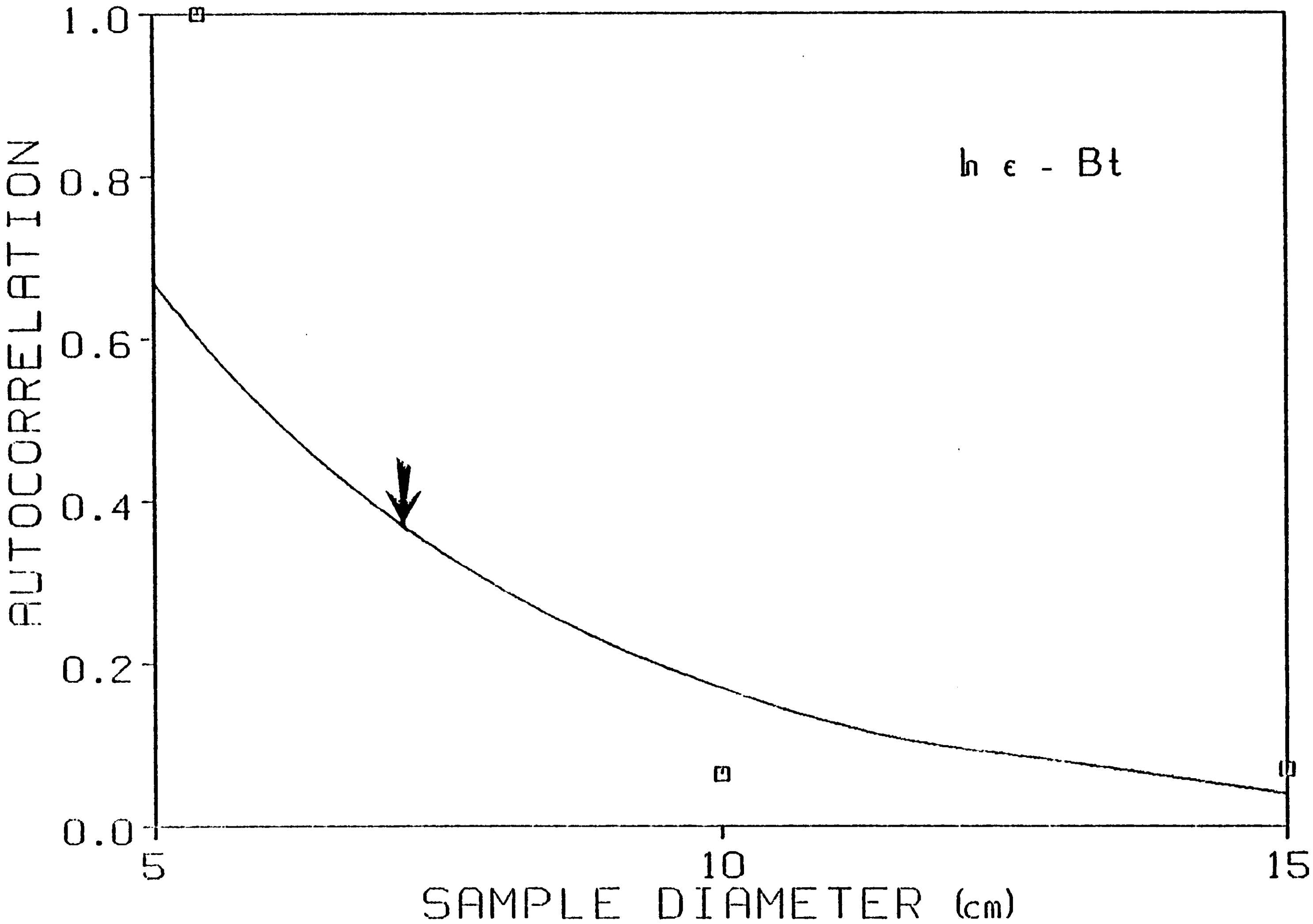

Figure 15: Autocorrelation of lnε for the B horizon. Arrow denotes integral scale.

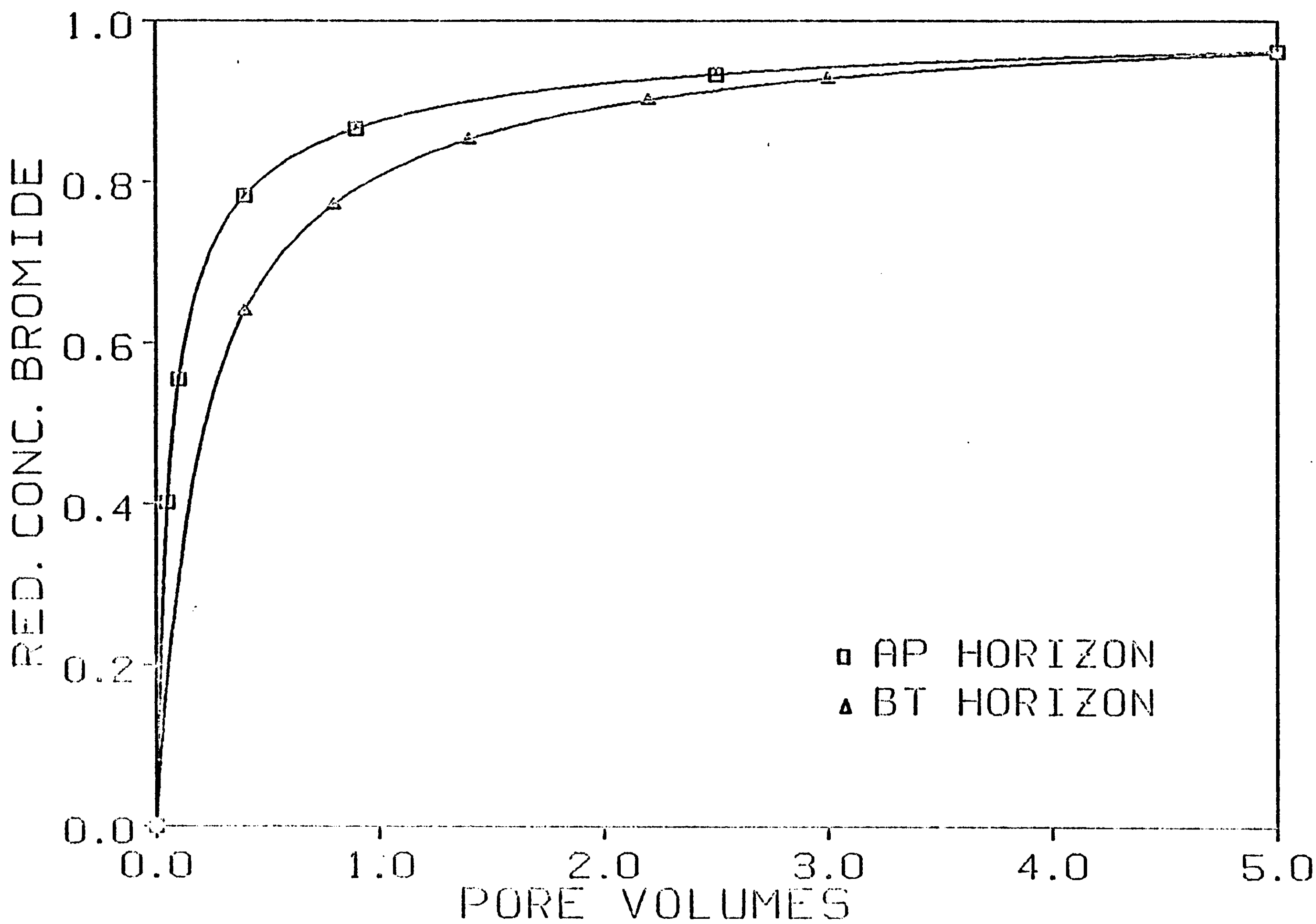

Figure 16: Average breakthrough curves for large cores comparing the effect of depth (n=19).

0.55 for Ap cores and 0.31 for Bt cores. Macropores in the clay Bt horizon are due to moderate aggregation.

Predicted Breakthrough Curves for the Field

Results from the Monte Carlo simulation are shown graphically for A and B horizons (Figures 17 and 18). BTC for the different core sizes in the A horizon are very similar. This is a convenient result since it suggests that different sample volumes may yield similar field predictions from stochastic analysis as long as the sample population is adequately large. Solute breakthrough is predicted to be extremely rapid with relative concentrations of 0.64, 0.65, and 0.72 for small, medium, and large cores at T=0.05. This is a striking contrast to the average BTC's calculated from the small observed population of 19 samples (corresponding values are 0.05, 0.22, and 0.40). Since the population distributions for the random variables are identical to the observed data, it appears that the effect of increasing n plays a significant role by including more of the extreme high and low values and the high v values exert a dominating influence on transport. Similarity in the three field curves may be partially explained by the long integral scale distance (105 mm) for K_s. At the core scale these volumes are fairly correlated to each other and therefore may be ex-

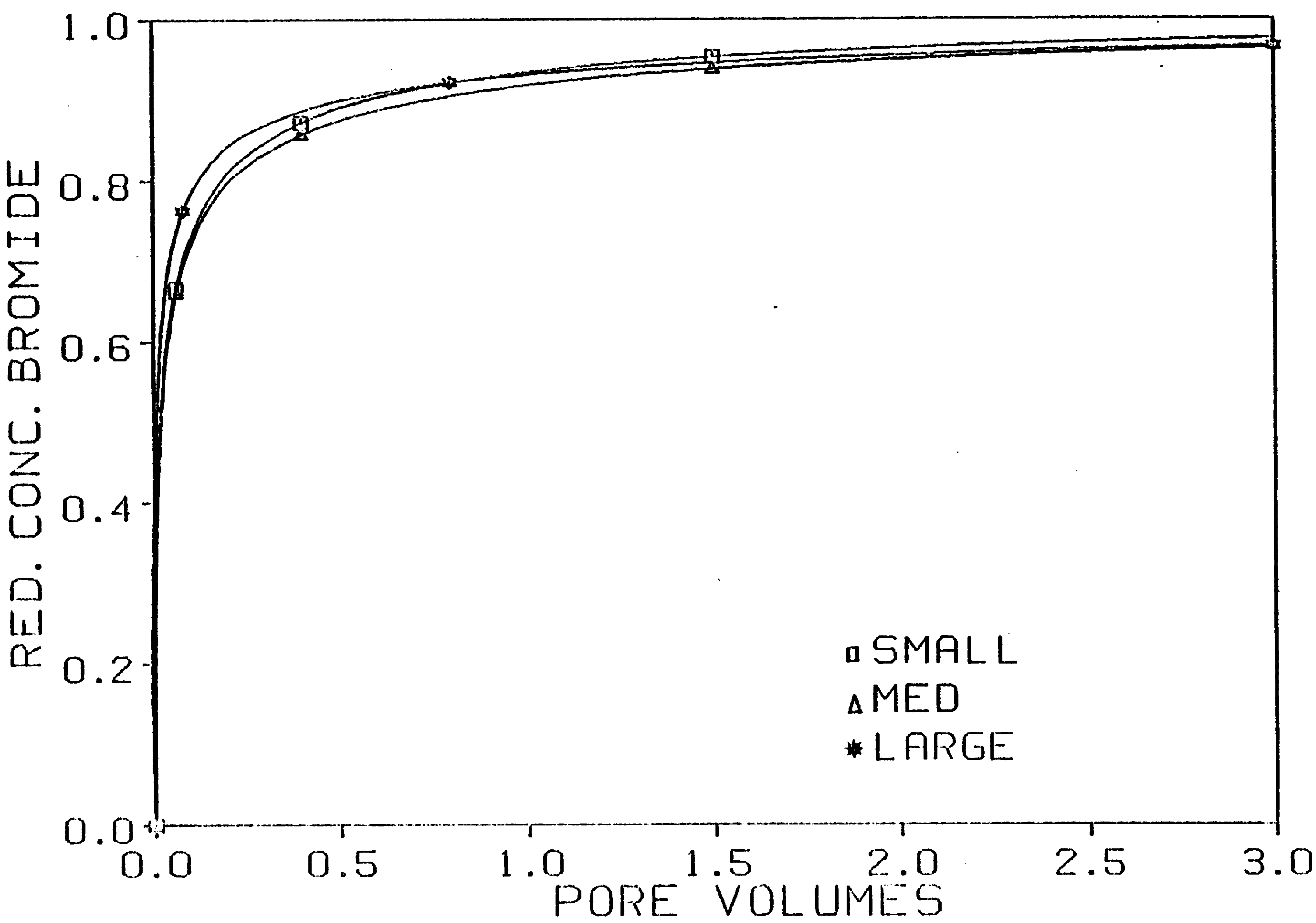

Figure 17: Field BTC's predicted from Monte Carlo analysis for all core sizes in Ap horizon,(n=5000).

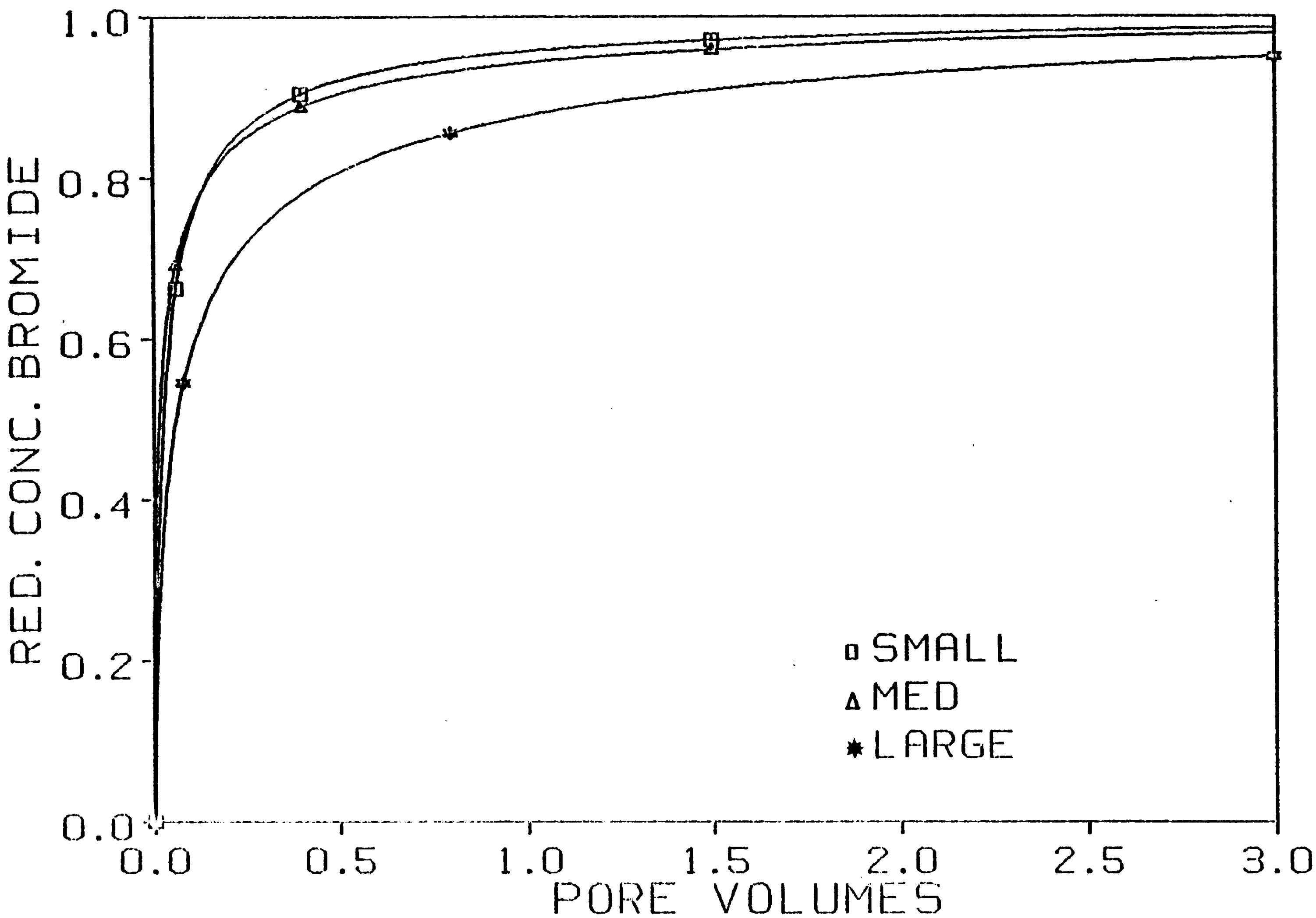

Figure 18: Field BTC's predicted from Monte Carlo analysis for all core sizes in Bt horizon,(n=5000).

pected to exhibit similar behavior from a stochastic analysis which simulates moments since both are dependent on variance.

In the Bt horizon solute breakthrough is again extremely rapid with reduced concentrations of 0.63, 0.69, and 0.47 for small, medium, and large cores at T=0.05. An intriguing but puzzling result from these curves is the substantially delayed breakthrough predicted for large cores relative to the small and medium cores which appear to be essentially identical. Additional confusion arises when comparisons are made with trends seen in mean BTC's calculated for the sample population directly for which large and medium cores yielded identical BTC's shifted to higher concentrations than the small cores. It may not be reasonable or valid to expect that these two approaches would show the same trends or that the stochastic approach will always yield similar field predictions regardless of the core size. Intuitively, increasing the sample number provides a better estimate of real solute behavior so it is likely that solute movement in the field would more closely follow the rapid breakthrough predicted by the Monte Carlo analysis. Nineteen cores are assumed to be an adequate number to describe the population statistics. Differences in the trends of observed versus predicted BTC may be explained by differing variances of transport parameters for the three core sizes. Large cores have about half as much variance in lnv (1.9) as the medium and small cores (4.1 and 4.5). As a consequence, more values of v are generated in the low probability tails of the probability distribution function for the Monte Carlo method than are actually observed from the small sample size of 19. Similarly extreme values are generated for smaller cores which show higher dispersion about the mean than low variance large cores. Truncating v and D to within 3.9 standard deviations for maximum and minimum values yielded identical results as having no limits. Due to the v weighting of the average concentration calculation, this makes the BTC predicted for the small cores higher than the large cores. Interpretation of these stochastically predicted field-average BTC's must be done cautiously. More confidence is placed in the large core data because it has the lowest variance. It also is more appealing to see the field BTC for the Bt horizon lower than that for the Ap due to the lower conductivity in the Bt horizon; large cores indicate this. Another factor that might help explain these differences is the shorter integral scales in the Bt horizon for K_s (9.9cm) and especially for ε (7.2cm). This suggests that the different core sizes are not necessarily similar to each other since autocorrelation drops off rapidly with increasing core size. A consideration in interpretting these results and justifying use of large core data lies in the basic assumptions in the derivation of concentration. Flow is assumed to be only in the vertical direction within a uniform streamtube and neighboring streamtubes do not interact. Realistically there is lateral mixing and vertical soil variation. Therefore it seems more reasonable to use large core estimates because lateral mixing between them will be lower. Small cores may be more susceptible to erroneously weighted high v values. One possible explanation for the differences between field-average BTC's is that longer cores are also incorporating more vertical heterogeneities. Also BTC's represent homogeneous profiles for A and B horizons independently. A more realistic approach would be to couple the A and B horizons using a 4x4 covariance matrix for v and D in both layers. Solute breakthrough for coupled horizons would be much slower.

Borrowing ergodicity concepts may be useful for evaluating the simulated BTC's in a speculative manner. Suppose that any given sample of any particular core size comes from an ensemble of all possible core sizes which together constitute a stationary, ergodic random process (a stationary process which is ergodic additionally stipulates that any one sample function, or core size in this case, is completely representative of the process as a whole). This assumption may be reasonable since the correlation scale for ε is much less than the field scale (25 versus 150 m). Ideally to test this hypothesis we would discretize the field into equal-sized samples repeatedly for each core size, calculate sample averages for each core size and examine how these core size averages compare with each other and with the corresponding average for the whole field. Since we did not measure solute behavior of the whole field, our theories must remain so. However from this perspective, we would not expect the average predicted BTC's for each core size to be exactly the same as the overall field average because the sample average only approaches the ensemble average when the sample volume approaches the field volume. For smaller volumes we would naturally expect some difference from the ensemble average. The remaining question is how much variation from one core size to the next is acceptable while still being consistent with the hypothesis that the total field volume is taken from a stationary ergodic ensemble.

Typically in time (or space)-series studies, spectral analysis is used to evaluate the data and then accuracy is determined by constructing confidence limits. Whether this approach is plausible for solute BTC's is a topic for further investigation. Solute concentrations may be somewhat cyclic laterally owing to the distributions of large pore sequences and subsequent zones of higher concentration (Bouma, 1981). Spectral analysis may be useful for quantifying these cyclic variations. Basically the procedure consists of calculating the autocorrelation relationship and then determining the spectral density function by means of a Fourier transform on the autocorrelogram. Power spectrums yield information useful in isolating periodicities or spacings associated with repetitious observations or properties such as larger pore sequences by the shape of the graph. Effects of sample size or spacing show up as frequency differences (larger samples at the same spacing show smaller frequencies than small samples). Therefore it seems feasible that spectral analysis would be useful in distinguishing sample size and macropore effects at the field scale, but only for observed data and not for comparison of stochastically generated BTC's.

Comparison of concentrations calculated from the deterministic parameters from the 19 sample sites at some selected depths using spectral analysis might be one possible approach. However paucity of sample number would likely restrict conclusions that could be drawn. Therefore spectral analysis is not attempted in this study nor do we attempt to prove stationarity because it would require many samples from line transects in multiple directions. Bouma (1981) utilized spectral analysis in their evaluation of field measured solute concentrations.

A larger question not explicitly addressed in this analysis is the 'meaningfulness' of field-scale predictions extrapolated from lab-scale data. Simmons (1982) and others (Freeze and Cherry, 1979) assert that the influence of long-range structural patterns may make this applicability uncertain.

GEOSTATISTICS

Semivariograms are shown for $\ln K_s$ and lnD for A and B horizons for all core sizes in Figures 19-22. There is a trend for most core sizes to show a range of about 25 m for $\ln K_s$ in the Ap horizon. This result is in agreement with many others (Kool et al., 1984 (25-30 m); Bresler et al., 1984 (20 m); Russo, 1983 (40 m); Russo and Bresler, 1981 (25 m); and Vieira et al., 1981 (20 m)). In regard to sampling, this suggests that except for replicates, samples should be spaced greater than 25 m apart to ensure random sampling. At shorter lags K_s may be spatially dependent. Medium core data show a flat $\gamma(h)$ semivariogram indicating an apparent "pure nugget" effect (Journel and Huijbregts, 1978) ie. variance is constant at all lags and even at the origin. If

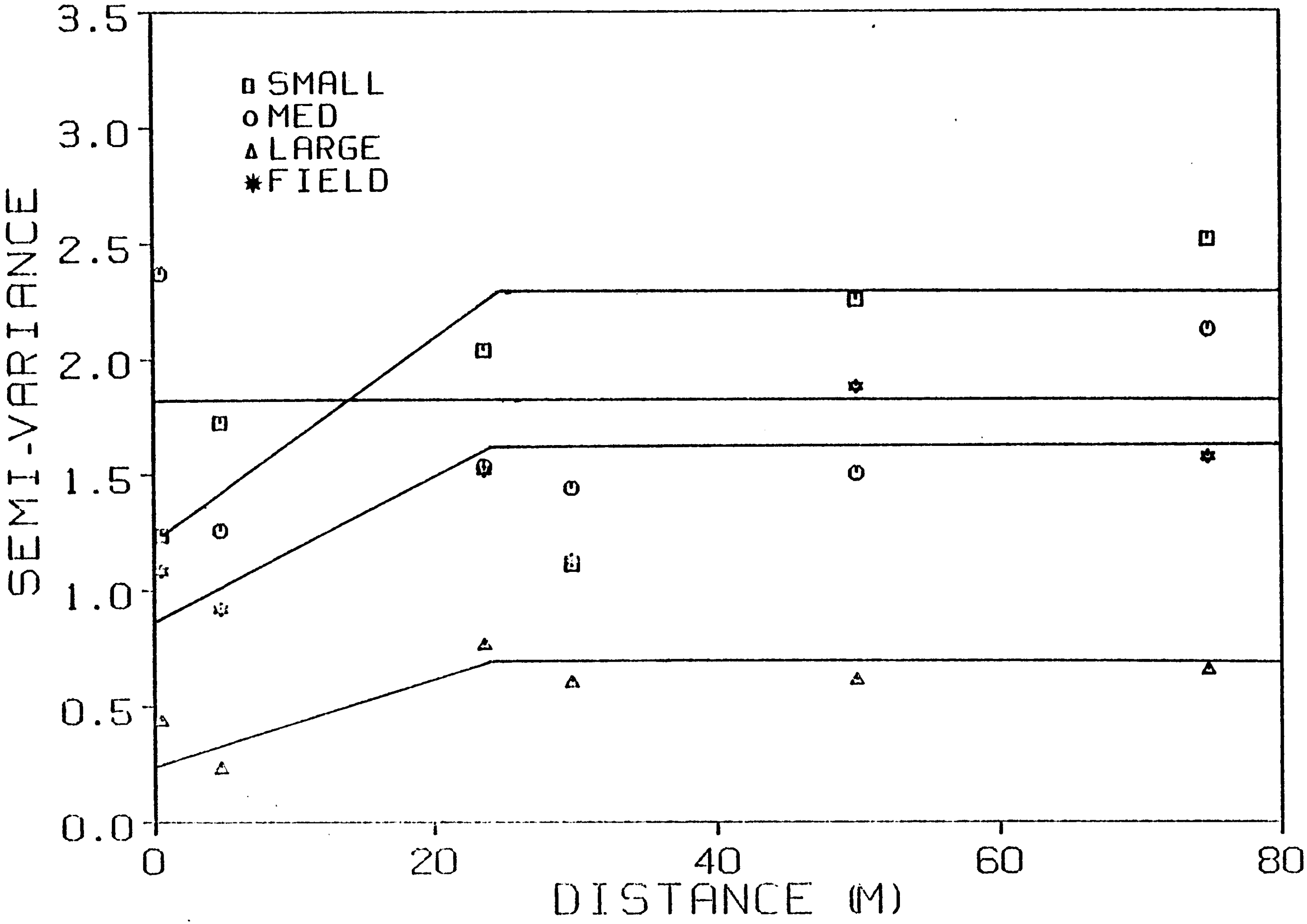

Figure 19: Semivariograms for lnK s measured from three core sizes and in-situ for the Ap horizon.

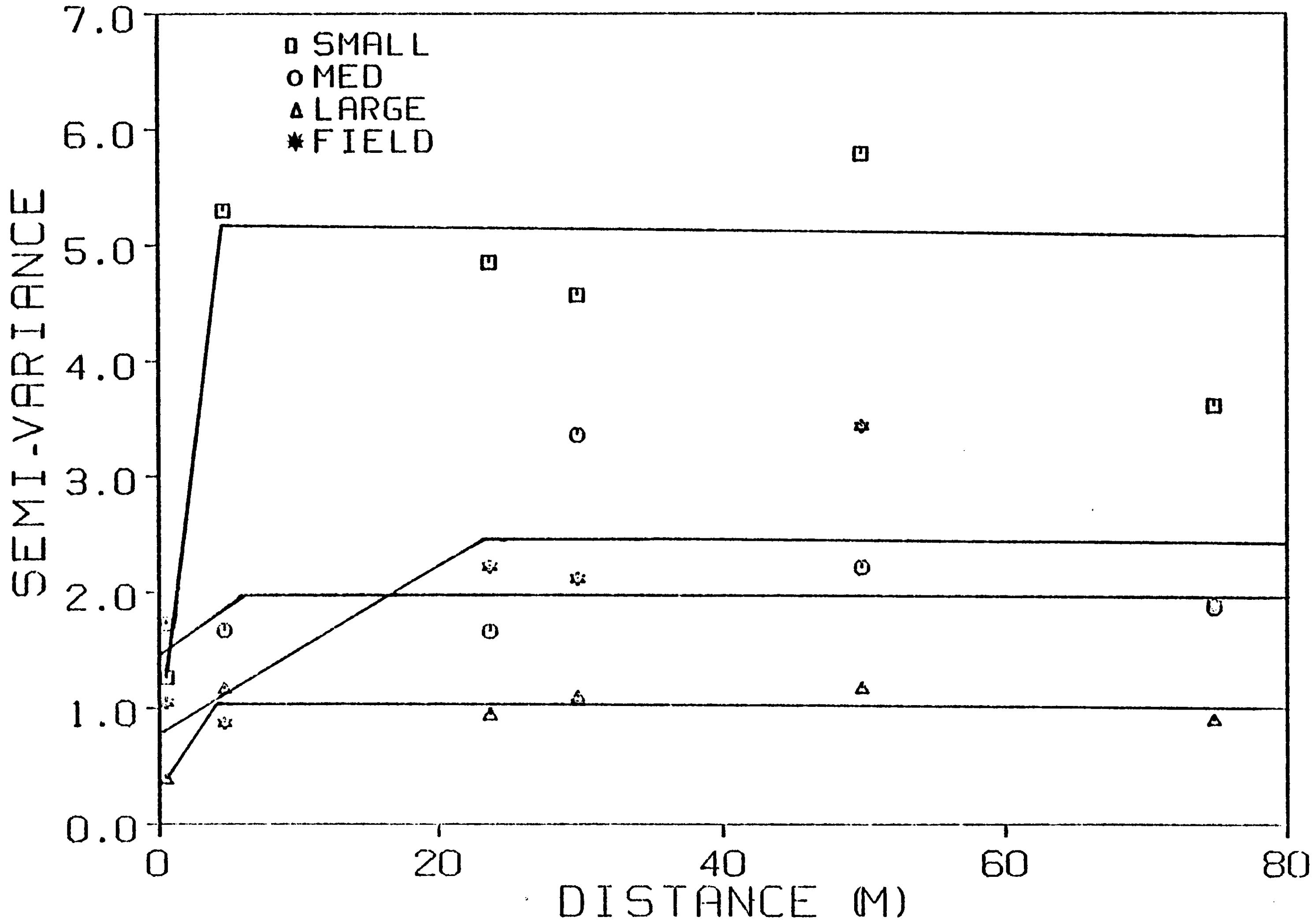

Figure 20: Semivariograms for $\ln K_s$ measured from three core sizes and in-situ for the Bt horizon.

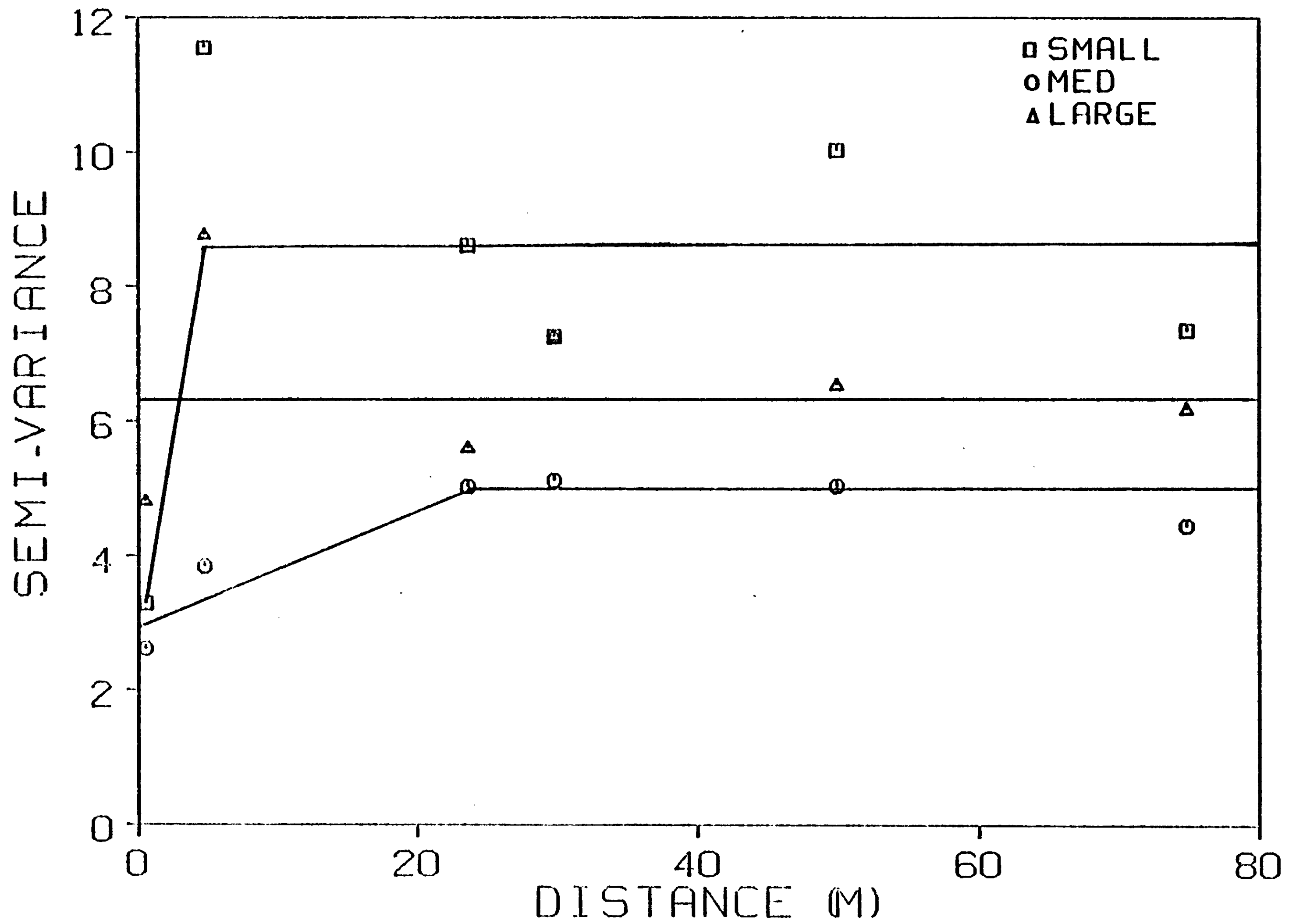

Figure 21: Semivariograms for lnD for three core sizes for the Ap horizon.

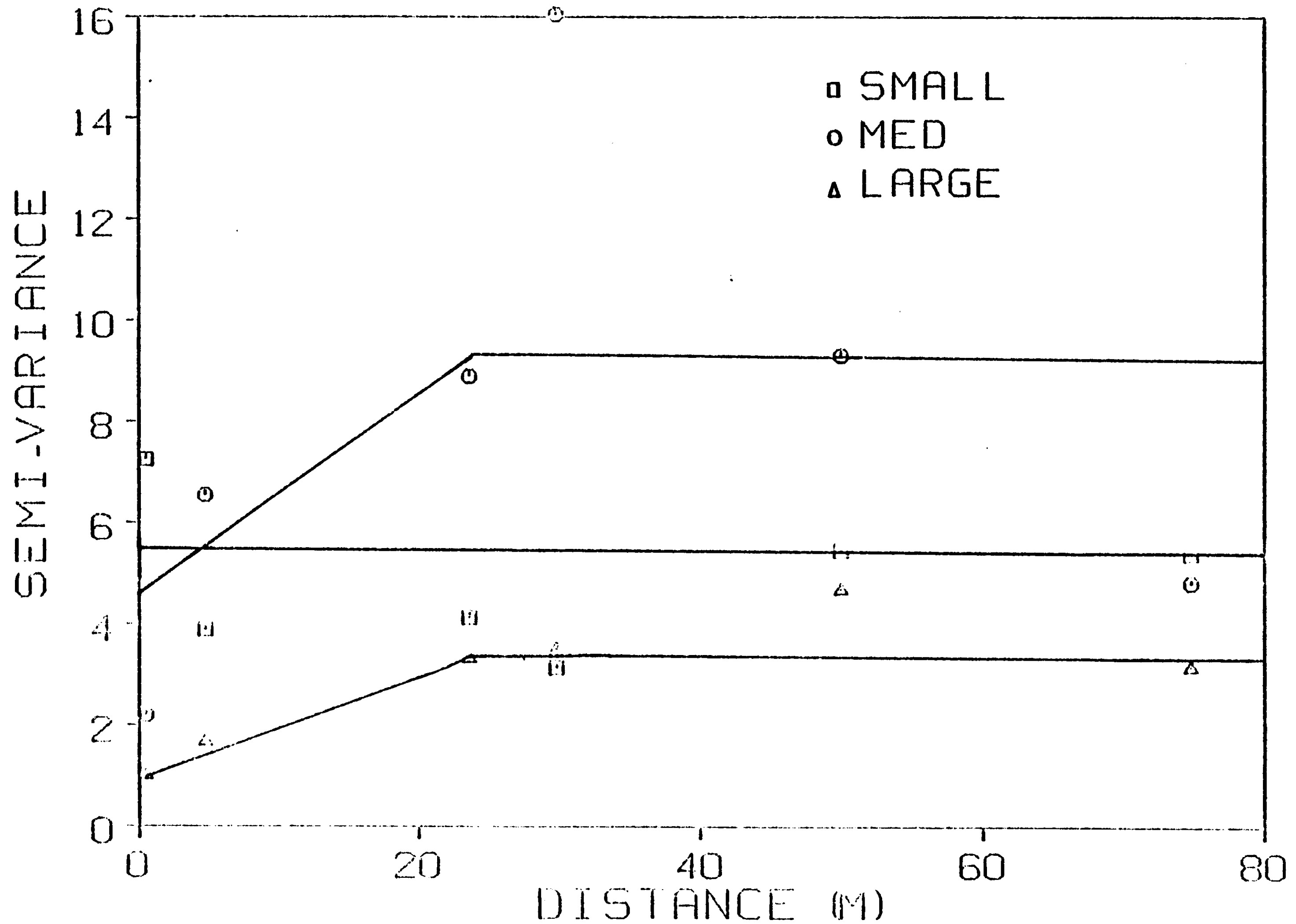

Figure 22: Semivariograms for lnD for three core sizes for the Bt horizon.

this were really the case then the field would be extremely homogeneous (at least at the scale of 0.5 m). But pure nuggets are rare and this result is more reasonably explained in light of the enormous scatter in the data. Ninety percent confidence intervals on $\gamma(h)$ are very large, especially at short sample separation distances. At h=0.5 m , γ may range from 1.1-10.3 and at h=4.75 m, γ may range from 0.7-3.0. Therefore little confidence is placed in the exact behavior of the variance at short lags and it is doubtful that the field is homogeneous. Erratic behavior (often due to too few data) is one of the main problems with constructing and interpreting semivariograms especially for highly variable properties like hydraulic conductivity. Russo (1984) points out that most geostatisticians regard 100 samples evenly distributed as a minimum requirement for the estimation of the semivariogram. One study had 200 data points and still a reliable semivariogram could not be obtained. Gelhar (1982) used spectral analysis to show wide confidence intervals and a relatively large uncertainty in the integral scale (of at least 50%) for the log-permeability and porosity data of Bakr (1976). Because of the low sample number it is difficult to draw definite conclusions from these semivariograms. It also precludes the possibility of omitting any outliers from the analysis. However we may feel reasonably confident in estimating the range as 25 m since the fitted lines reflect the mean $\gamma(h)$ relationship and are therefore the best estimates of the variance structure and because most of the data support this trend. Smaller core graphs are displaced upward from the large core graphs due to higher sample variance. Sill variances shown in the figure are similar to observed variances from classical statistical analyses.

Semivariograms for $\ln K_s$ in the Bt horizon show a lack of spatial dependence for all core sizes (Figure 20). Finite population variance is reached at very short distances (about 5-7 m). Field data however show a range of about 20 m. Reasons for this difference are not readily apparent. Sample spacing in the Bt horizon does not appear to be an important consideration, however, conservatively it might be desirable to space these samples 20-25 m apart as indicated by the in-situ variogram. This would also coincide with the spacing for the A horizon. Russo and Bresler (1981) found the same general trend of increasing coefficients of variation and decreasing ranges for conductivity with depth; they used the autocorrelation method to determine ranges of about 25, 24, 14 and 11 m for 0, 0.3, 0.6 and 0.9 m depths for diffusivity $(K(\theta)/(d\theta/dh))$.

Structure of variance in the field was also analyzed for solute dispersion coefficients (Figures 21 and 22). Ranges for both horizons appear to be around 25 m. Some exceptions to this trend are large and small cores in the A horizon and small cores in the Bt horizon, but the confidence intervals for these semivariograms are very high for short lags. At h=4.75 m, γ may range from 6.5-27.8 for small A cores; at h=0.5 m, γ may range from 2.2-21.0 for large A cores; and at h=29.75 m, γ may range from 8.5-43.5 for small B cores.

CONCLUSIONS

Solute transport through undisturbed cores of a Groseclose soil containing macropores may be adequately described using a monocontinuum model. Mean errors of reduced concentration are less than or equal to 0.07 for 80% of the samples. This error value is considered satisfactory in light of high field-scale spatial variability. Predicted breakthrough curves using a bicontinuum model agree very well with observed BTC's; mean fitting errors are less than or equal to 0.07 for 97% of the samples. Physically uninterprettable beta and omega parameter estimates were obtained for the two-region model. The monocontinuum model was chosen to estimate dispersion coefficients for all samples used in the statistical comparisons of core volumes.

Sample volumes between the range of 471-1767 cm^3 do not significantly affect observed bulk density or moisture retention characteristics in either Ap or Bt horizons of the soil studied. No significant differences in total porosity are detected and pore size distributions for the three sample volumes are similar. Coefficients of variation of these properties are low (7-20%).

Saturated hydraulic conductivity is significantly influenced by sample volume since it is governed by pore continuity and is related to the square pore size. Increasing sample volume results in decreasing variance of K_s in both horizons because larger samples incorporate more of the field heterogeneity and have a lower proportion of the core volume subject to disturbance. Conductivities decrease and exhibit higher variance with depth. Coefficients of variation are high (60-155%). Short-range mutual dependence between core sizes is described as a first- order autoregressive process with integral scales of about 100 mm for $\ln K_s$ in both horizons.

Solute transport parameters are even more sensitive to sample volume than K_s. The integral scale for dispersivity is about 70 mm showing low autocorrelation between a short range of sample sizes. Presence of large continuous pores is seen from rapid bromide elution suggesting that influent bypasses much of the resident liquid. Complicated pore geometries are deduced from highly variable dispersivities. Large cores have higher pore water velocities, dispersion coefficients, and dispersivities with lower variance than smaller cores implying that they contain a wider range of pore sizes and more continuous macropores. Large cores are less disturbed and are more reflective of the field. In the Bt horizon, small cores are impractical and inaccurate for assessing solute transport parameters and although parameters for the medium and large cores are statistically different, the mean breakthrough curves become identical when concentrations are weighted by their local pore water velocities since the faster pores dominate solute behavior. Coefficients of variation for v and D are very high (70-280%).

Field predicted solute breakthrough curves are similar for different core sizes in the Ap horizon. Solute transport is predicted to be much more rapid when the sample population has been increased using the Monte Carlo method than when only 19 samples are averaged. This is due to the influence of high v values weighting the calculated concentrations. Solute behavior in the Bt horizon may be affected by sample size. Small and medium cores had similarly more rapid breakthrough than the large cores, however, it is believed that the large cores yield a more accurate estimate for the field because of their lower variance and inclusion of more lateral dispersion and vertical heterogeneity. Uncertainty in the meaningfulness of extrapolation of lab-scale data to the field-scale places restrictions on the applicability of these predictions.

Semivariograms for $\ln K_s$ and lnD show ranges of 25m for the Ap horizon and shorter ranges (5-25m) for the Bt horizon. The same sampling scheme would be adequate for both parameters. Twenty-five meter sample separation distances are recommended to ensure random sampling. Much scatter was observed probably due to too few data. High confidence limits especially at short lags resulted.

SUMMARY

Monocontinuum modelling of solute transport for the purpose of making field predictions is considered adequate for the aggregated Groseclose soil used in this study. Bi-continuum modelling often results in large uncertainty in its two additional fitted parameters, beta and omega. Sample volume is not a consideration for measuring the low variation physical properties bulk density and $\theta(h)$. 'Large' undisturbed cores are recommended for assessing high variation fluid transport parameters K_s, v, D, and ε since they provide a more accurate representation of the field. Distance between samples should be at least 25 m to guarantee random and independent samples for estimating saturated hydraulic conductivity and dispersion coefficients. Field-average breakthrough curves predicted from a Monte Carlo analysis show that the three core sizes used in this study predict similar solute behavior in the Ap horizon when a large number of observations are used. In the Bt horizon, field-average breakthrough curves are more accurately predicted by large cores.

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APPENDIX A

MOISTURE RETENTION AND BULK DENSITY FOR SMALL AP HORIZON CORES

DEPTH=Ap VOL=Small

		Head Equivalent Matric Tension (m)							
CORE	BULKD	0.00	0.10	0.50	1.00	3.00	6.00	10.00	Field
1	1.194	0.515	0.456	0.398	0.370	0.332	0.302	0.274	0.335
2	1.211	0.542	0.457	0.381	0.353	0.319	0.290	0.264	0.267
3	1.418	0.480	0.434	0.383	0.363	0.332	0.306	0.283	0.321
4	1.365	0.432	0.473	0.415	0.390	0.357	0.331	0.309	0.358
5	1.400	0.442	0.416	0.386	0.357	0.320	0.295	0.274	0.194
6	1.406	0.477	0.483	0.401	0.374	0.339	0.312	0.290	0.317
7	1.238	0.474	0.404	0.349	0.331	0.312	0.299	0.286	0.332
8	1.503	0.386	0.425	0.385	0.370	0.343	0.322	0.304	0.348
9	1.432	0.439	0.424	0.409	0.394	0.365	0.342	0.318	0.368
10	1.437	0.467	0.403	0.374	0.347	0.312	0.291	0.279	0.300
11	1.515	0.444	0.424	0.390	0.361	0.318	0.289	0.271	0.287
12	1.586	0.407	0.430	0.385	0.363	0.335	0.316	0.298	0.326
13	1.625	0.404	0.373	0.344	0.333	0.313	0.298	0.285	0.306
14	1.571	0.442	0.407	0.373	0.355	0.325	0.301	0.286	0.331
15	1.568	0.407	0.397	0.373	0.355	0.332	0.307	0.298	0.321
16	1.499	0.455	0.394	0.379	0.368	0.342	0.340	0.325	0.350
17	1.407	0.447	0.400	0.368	0.339	0.308	0.287	0.263	0.326
18	1.575	0.401	.	.	.	.	.	.	.
19	1.564	0.436	0.392	0.375	0.365	0.343	0.322	0.301	0.253
Mean	1.448	0.447	0.422	0.382	0.360	0.330	0.308	0.289	0.313
SD	0.129	0.040	0.030	0.018	0.017	0.016	0.017	0.018	0.042

APPENDIX B

MOISTURE RETENTION AND BULK DENSITY FOR MEDIUM AP HORIZON CORES

DEPTH=Ap VOL=Med

		Head Equivalent Matric Tension (m)							
CORE	BULKD	0.00	0.10	0.50	1.00	3.00	6.00	10.00	Field
1	1.358	0.477	0.450	0.436	0.398	0.391	0.369	0.352	0.231
2	1.293	0.538	0.482	0.448	0.394	0.370	0.337	0.318	0.215
3	1.317	0.503	0.474	0.421	0.383	0.377	0.366	0.356	.
4	1.520	0.532	0.499	0.477	0.462	0.427	0.396	0.368	0.506
5	1.447	0.447	0.444	0.421	0.382	0.375	0.361	0.337	0.182
6	1.355	0.496	0.442	0.413	0.371	0.361	0.336	0.321	0.206
7	1.455	0.451	0.383	0.373	0.331	0.323	0.306	0.294	.
8	1.391	0.469	0.415	0.389	0.343	0.329	0.310	0.290	0.242
9	1.430	0.448	0.424	0.413	0.375	0.363	0.343	0.332	0.254
10	1.488	0.439	0.426	0.410	0.385	0.378	0.357	0.338	0.320
11	1.545	0.396	0.394	0.394	0.330	0.318	0.303	0.288	0.280
12	1.501	0.408	0.399	0.399	0.364	0.349	0.331	0.311	0.283
13	1.633	0.390	0.377	0.377	0.343	0.335	0.312	0.290	0.277
14	1.514	0.425	0.392	0.376	0.359	0.336	0.318	0.308	0.267
15	1.414	0.429	0.415	0.408	0.380	0.369	0.349	0.331	0.270
16	1.478	0.407	0.396	0.379	0.365	0.332	0.292	0.264	0.242
17	1.468	0.432	0.414	0.405	0.374	0.367	0.351	0.337	0.244
18	1.611	0.393	0.375	0.375	0.333	0.322	0.304	0.286	0.217
19	1.637	0.378	0.359	0.359	0.337	0.325	0.309	0.293	0.228
Mean	1.466	0.445	0.419	0.404	0.369	0.355	0.334	0.317	0.263
SD	0.419	0.047	0.038	0.029	0.031	0.029	0.028	0.028	0.071

APPENDIX C

MOISTURE RETENTION AND BULK DENSITY FOR LARGE AP HORIZON CORES

DEPTH=Ap VOL=Large

		HEAD EQUIVALENT MATRIC TENSION (M)							
CORE	BULKD	0.00	0.10	0.50	1.00	3.00	6.00	10.00	FIELD
1	1.145	0.494	0.441	0.420	0.402	0.359	0.298	0.298	0.382
2	1.241	0.516	0.463	0.410	0.372	0.334	0.305	0.269	0.318
3	1.330	0.495	0.469	0.414	0.407	0.387	0.364	0.333	0.406
4	1.380	0.471	0.444	0.431	0.413	0.373	0.334	0.298	.
5	1.290	0.485	0.459	0.450	0.428	0.385	0.344	0.305	0.409
6	1.232	0.500	0.465	0.393	0.379	0.375	0.362	0.331	0.413
7	1.377	0.448	0.407	0.392	0.385	0.372	0.344	0.327	0.362
8	1.430	0.435	0.419	0.398	0.377	0.342	0.312	0.279	0.363
9	1.347	0.471	0.448	0.401	0.393	0.376	0.342	0.313	0.434
10	1.368	0.456	0.430	0.427	0.416	0.376	0.342	0.315	0.432
11	1.441	0.483	0.456	0.450	0.430	0.374	0.332	0.303	0.432
12	1.330	0.450	0.403	0.345	0.339	0.324	0.305	0.288	0.329
13	1.551	0.390	0.348	0.348	0.326	0.300	0.275	0.260	0.306
14	1.670	0.425	0.380	0.361	0.347	0.317	0.291	0.269	0.340
15	1.487	0.450	0.410	0.407	0.394	0.362	0.333	0.308	0.356
16	1.325	0.443	0.395	0.378	0.363	0.331	0.302	0.272	0.332
17	1.287	0.441	0.391	0.358	0.354	0.340	0.316	0.295	0.355
18	1.450	0.403	0.372	0.359	0.324	0.280	0.254	0.230	0.271
19	1.530	0.422	0.396	0.396	0.379	0.351	0.322	0.301	0.369
MEAN	1.380	0.457	0.421	0.397	0.380	0.350	0.320	0.294	0.367
SD	0.125	0.034	0.035	0.032	0.032	0.030	0.029	0.026	0.047

APPENDIX D

MOISTURE RETENTION AND BULK DENSITY FOR SMALL BT HORIZON CORES

DEPTH=Bt VOL=Small

		Head Equivalent Matric Tension (m)							
CORE	BULKD	0.00	0.10	0.50	1.00	3.00	6.00	10.00	Field
1	1.403	0.427	0.417	0.402	0.398	0.390	0.387	0.384	0.374
2	1.405	0.462	0.444	0.428	0.424	0.415	0.409	0.405	0.391
3	1.158	0.483	0.453	0.430	0.426	0.417	0.411	0.407	0.349
4	1.438	0.461	0.449	0.432	0.429	0.419	0.412	0.406	0.402
5	1.314	0.452	0.449	0.461	0.461	0.459	0.453	0.451	0.393
6	1.281	0.432	0.413	0.393	0.389	0.376	0.365	0.355	0.351
7	1.193	0.424	0.406	0.384	0.379	0.369	0.366	0.366	0.354
8	1.215	0.421	0.410	0.386	0.381	0.372	0.366	0.357	0.362
9	1.361	0.406	0.384	0.366	0.361	0.351	0.348	0.343	0.334
10	1.601	0.347	0.347	0.347	0.339	0.310	0.290	0.260	0.173
11	1.619	0.439	0.419	0.394	0.368	0.339	0.314	0.290	0.194
12	1.547	0.385	0.384	0.356	0.343	0.325	0.314	0.300	0.245
13	1.519	0.330	0.330	0.330	0.327	0.319	0.316	0.313	0.330
14	1.644	0.334	0.334	0.334	0.330	0.324	0.321	0.312	0.327
15	1.445	0.362	0.355	0.339	0.335	0.327	0.324	0.320	0.341
16	1.457	0.419	0.419	0.400	0.394	0.386	0.380	0.376	0.384
17	1.453	0.406	0.368	0.345	0.338	0.327	0.320	0.314	0.336
18	1.443	0.351	0.338	0.392	0.387	0.378	0.376	0.373	0.322
19	1.325	0.480	.	.	.	.	.	.	0.414
Mean	1.412	0.412	0.396	0.384	0.378	0.367	0.360	0.352	0.336
SD	0.141	0.048	0.042	0.038	0.039	0.042	0.044	0.049	0.065

APPENDIX E

MOISTURE RETENTION AND BULK DENSITY FOR MEDIUM BT HORIZON CORES

DEPTH=Bt VOL=Med

CORE	BULKD	Head Equivalent Matric Tension (m) 0.00	0.10	0.50	1.00	3.00	6.00	10.00	Field
1	1.540	0.396	0.387	0.365	0.362	0.354	0.345	0.335	0.335
2	1.586	0.454	0.444	0.427	0.421	0.411	0.399	0.388	0.392
3	1.531	0.432	0.421	0.393	0.391	0.382	0.372	0.361	0.350
4	1.392	0.455	0.443	0.430	0.424	0.413	0.401	0.391	.
5	1.467	0.476	0.460	0.447	0.442	0.435	0.425	0.418	0.426
6	1.421	0.473	0.403	0.384	0.376	0.356	0.337	0.318	0.316
7	1.612	0.405	0.389	0.376	0.369	0.355	0.344	0.334	0.335
8	1.475	0.408	0.396	0.385	0.376	0.364	0.351	0.338	0.339
9	1.577	0.419	0.414	0.403	0.397	0.386	0.374	0.361	0.368
10	1.677	0.318	0.306	0.282	0.271	0.258	0.247	0.232	0.251
11	1.738	0.349	0.318	0.294	0.282	0.272	0.260	0.246	0.248
12	1.712	0.360	0.347	0.347	0.344	0.330	0.316	0.303	0.337
13	1.685	0.367	0.345	0.337	0.329	0.316	0.305	0.293	0.296
14	1.668	0.387	0.349	0.326	0.318	0.307	0.295	0.282	0.313
15	1.666	0.387	0.372	0.355	0.341	0.331	0.319	0.311	0.309
16	1.642	0.378	0.347	0.295	0.285	0.270	0.259	0.250	0.302
17	1.607	0.366	0.364	0.357	0.348	0.336	0.325	0.313	0.319
18	1.722	0.344	0.333	0.313	0.305	0.296	0.288	0.280	0.282
19	1.285	0.505	0.496	0.496	0.483	0.470	0.456	0.444	0.440
Mean	1.579	0.404	0.386	0.369	0.361	0.350	0.338	0.326	0.331
SD	0.125	0.051	0.051	0.056	0.057	0.058	0.057	0.058	0.052

APPENDIX F

MOISTURE RETENTION AND BULK DENSITY FOR LARGE BT HORIZON CORES

DEPTH=Bt VOL=Large

		Head Equivalent Matric Tension (m)							
CORE	BULKD	0.00	0.10	0.50	1.00	3.00	6.00	10.00	Field
1	1.145	0.494	0.451	0.435	0.425	0.406	0.394	0.383	0.381
2	1.538	0.421	0.415	0.409	0.399	0.383	0.373	0.364	0.374
3	1.421	0.476	0.441	0.411	0.399	0.384	0.373	0.364	0.367
4	1.393	0.479	0.452	0.441	0.433	0.413	0.396	0.378	0.403
5	1.443	0.473	0.439	0.429	0.419	0.405	0.397	0.389	0.407
6	1.463	0.445	0.424	0.407	0.397	0.380	0.369	0.359	0.371
7	1.504	0.402	0.380	0.367	0.353	0.335	0.321	0.309	0.338
8	1.480	0.442	.	0.347	0.333	0.310	0.296	0.288	0.350
9	1.581	0.386	0.363	0.353	0.340	0.320	0.307	0.294	0.311
10	1.574	0.346	0.327	0.304	0.291	0.272	0.258	0.241	0.276
11	1.433	0.400	0.356	0.334	0.306	0.275	0.246	0.215	0.261
12	1.547	0.389	0.377	0.372	0.365	0.350	0.335	0.318	0.351
13	1.628	0.332	0.321	0.309	0.299	0.282	0.270	0.256	0.280
14	1.609	0.362	0.336	0.311	0.305	0.288	0.278	0.267	0.278
15	1.637	0.362	0.330	0.307	0.301	0.284	0.270	0.255	0.275
16	1.645	0.380	0.329	0.290	0.281	0.263	0.251	0.239	0.306
17	1.667	0.335	0.300	0.272	0.260	0.241	0.227	0.218	0.254
18	1.643	0.361	0.341	0.321	0.310	0.293	0.279	0.257	0.307
19	1.343	0.464	0.459	0.444	0.436	0.420	0.410	0.386	0.443
Mean	1.510	0.408	0.380	0.361	0.350	0.332	0.318	0.257	0.307
SD	0.131	0.053	0.054	0.056	0.057	0.059	0.060	0.062	0.056

APPENDIX G

SATURATED HYDRAULIC CONDUCTIVITIES (MS^{-1}) FOR AP HORIZON

DEPTH=Ap

CORE	Small	Medium	Large	Field
1	2.90E-05	4.05E-05	4.91E-05	9.76E-05
2	1.84E-05	6.28E-05	1.37E-04	1.72E-05
3	5.86E-06	2.07E-04	9.54E-05	6.30E-05
4	1.52E-05	3.98E-06	6.20E-05	1.33E-05
5	3.66E-06	3.12E-04	2.28E-05	1.46E-06
6	2.63E-05	3.10E-05	7.70E-05	8.23E-06
7	2.67E-05	3.34E-04	1.38E-05	4.54E-06
8	9.58E-06	4.02E-05	1.73E-05	4.53E-06
9	8.25E-07	2.94E-05	3.14E-05	6.72E-07
10	2.13E-06	2.09E-05	7.37E-05	4.16E-06
11	3.90E-06	1.16E-04	6.14E-05	5.70E-06
12	7.08E-06	1.88E-05	5.30E-05	1.33E-05
13	3.28E-05	6.36E-05	4.41E-05	3.34E-06
14	1.67E-06	3.62E-06	1.93E-05	2.54E-05
15	2.16E-06	1.04E-05	2.33E-05	2.69E-06
16	7.44E-06	2.77E-06	4.72E-05	3.90E-06
17	3.15E-06	1.12E-05	1.26E-04	9.11E-06
18	1.60E-06	8.10E-05	8.34E-05	1.82E-05
19	4.69E-08	1.52E-06	1.72E-04	9.69E-07
Mean	1.00E-05	7.32E-05	6.36E-05	1.57E-05
Std.Dev.	1.02E-05	1.01E-04	4.39E-05	2.44E-05
Exp Mean	1.63E-05	9.70E-05	6.57E-05	1.64E-05

APPENDIX H

SATURATED HYDRAULIC CONDUCTIVITIES (MS^{-1}) FOR BT HORIZON

DEPTH=Bt

CORE	Small	Medium	Large	Field
1	2.18E-06	3.10E-07	4.36E-05	3.14E-07
2	3.17E-06	7.38E-08	1.00E-05	7.30E-08
3	1.68E-05	4.92E-07	4.02E-05	4.42E-07
4	9.74E-06	9.87E-07	7.34E-05	4.24E-06
5	1.09E-05	1.16E-06	5.64E-05	7.88E-07
6	6.22E-05	2.20E-05	3.68E-05	3.53E-07
7	1.14E-05	5.13E-06	7.15E-05	3.71E-06
8	2.15E-05	2.68E-06	3.59E-05	3.75E-06
9	1.04E-05	2.78E-06	7.24E-05	1.29E-05
10	8.17E-08	2.88E-06	5.94E-05	4.24E-06
11	6.75E-07	2.72E-07	1.03E-04	9.26E-07
12	2.72E-07	3.82E-06	3.10E-06	5.39E-07
13	4.12E-05	5.50E-07	3.75E-05	6.60E-08
14	1.40E-04	1.92E-06	3.57E-05	3.91E-07
15	4.23E-05	2.68E-06	5.16E-05	1.47E-07
16	5.35E-06	1.79E-05	3.26E-05	8.20E-07
17	7.68E-05	9.19E-07	4.21E-05	3.51E-06
18	9.94E-05	1.84E-06	9.95E-05	1.06E-06
19	1.26E-06	5.90E-07	3.34E-06	1.03E-07
Mean	2.92E-05	3.60E-06	4.78E-05	2.07E-06
Std.Dev.	3.93E-05	5.95E-06	2.79E-05	3.04E-06
Exp Mean	6.91E-05	3.95E-06	5.80E-05	2.44E-06

APPENDIX I

SOLUTE TRANSPORT PARAMETERS FOR SMALL AP HORIZON CORES

DEPTH=Ap VOL=Small

CORE	v(m/day)	D(m^2/d)	DISP(m)	P
1	6.48240	0.29125	0.044929	0.8902
2	2.24860	0.17610	0.078315	0.5108
3	0.09410	0.00250	0.026567	1.5056
4	4.63240	1.44850	0.312689	3.1981
5	9.26660	1.56703	0.169105	0.2365
6	1.11760	0.04046	0.036203	1.1049
7	4.24850	1.83290	0.431423	0.0927
8	0.07343	0.00625	0.085115	0.4700
9	3.09610	0.73646	0.237867	0.1682
10	1.40670	0.06354	0.045170	0.8856
11	1.17720	0.06648	0.056473	0.7083
12	0.01110	0.00016	0.014414	2.7750
13	0.17050	0.00990	0.058065	0.6889
14	0.04510	0.00097	0.021508	1.8598
15	4.65320	2.18900	0.470429	0.0850
16	7.33740	1.79510	0.244651	0.1635
17	2.66890	0.52917	0.198273	0.2017
18	0.54500	0.02834	0.052000	0.7692
19	0.19860	0.01702	0.085700	0.4667
Mean	2.60386	0.56848	0.140468	0.8831
Std.Dev	2.79711	0.77232	0.139819	0.8840
Exp.Mean	0.21298	4.12065	0.148128	

APPENDIX J

SOLUTE TRANSPORT PARAMETERS FOR MEDIUM AP HORIZON CORES

DEPTH=Ap VOL=Med

CORE	v(m/day)	D(m^2/d)	DISP(m)	P
1	0.9762	0.1195	0.12241	0.4697
2	15.4480	6.6017	0.42735	0.1303
3	9.9420	3.9513	0.39744	0.1510
4	3.8495	2.1894	0.56875	0.0997
5	0.9722	0.0684	0.07036	0.8144
6	8.2702	4.3934	0.53123	0.1081
7	23.4123	16.0886	0.68719	0.0873
8	10.3843	6.7694	0.65189	0.0876
9	5.9504	3.8198	0.64195	0.0900
10	13.9704	11.3715	0.81397	0.0721
11	4.2789	2.6878	0.62815	0.0928
12	0.3340	0.0306	0.09150	0.6363
13	5.3744	4.8321	0.89910	0.0649
14	9.9227	7.4183	0.74761	0.0781
15	3.4364	1.5598	0.45390	0.1295
16	10.5449	3.4080	0.32319	0.1863
17	5.4253	5.7031	1.05121	0.0560
18	7.8729	6.9300	0.88023	0.0658
19	0.0233	0.0029	0.12318	0.4775
Mean	7.3886	4.6287	0.53213	0.2051
Std.Dev	5.9256	4.1164	0.29189	0.2218
Exp.Mean	15.1238	24.3306	0.58950	

APPENDIX K

SOLUTE TRANSPORT PARAMETERS FOR LARGE AP HORIZON CORES

DEPTH=Ap VOL=Large

CORE	v(m/day)	D(m^2/d)	DISP(m)	P
1	6.2058	3.0260	0.48761	0.1567
2	8.1872	13.576	1.65824	0.0525
3	51.1062	88.883	1.73918	0.0482
4	12.3350	77.608	6.29172	0.0139
5	1.2330	0.325	0.26341	0.3519
6	0.8316	0.333	0.40052	0.2369
7	10.4452	20.994	2.00991	0.0430
8	8.3900	10.717	1.27736	0.0686
9	0.1275	0.011	0.08831	0.9812
10	1.5713	0.493	0.31349	0.3011
11	5.5600	25.963	4.66957	0.0171
12	2.2926	2.033	0.88664	0.1003
13	6.5987	4.304	0.65230	0.1165
14	87.9300	69.401	0.78928	0.0112
15	1.6551	0.456	0.27571	0.2946
16	51.0130	109.577	2.14802	0.0365
17	11.6139	30.918	2.66220	0.0380
18	3.3288	2.027	0.60888	0.1498
19	4.0673	4.071	1.00080	0.0883
Mean	14.4470	24.458	1.48543	0.1640
Std.Dev	23.1746	34.804	1.60677	0.2237
Exp.Mean	17.8198	92.853	1.60120	

APPENDIX L

SOLUTE TRANSPORT PARAMETERS FOR SMALL BT HORIZON CORES

DEPTH=Bt VOL=Small

CORE	v(m/day)	D(m^2/d)	DISP(m)	P
1	0.0011	0.00034	0.3091	0.1294
2	0.0011	0.00001	0.0091	4.4000
3	0.0173	0.00053	0.0306	1.3055
4	0.0081	0.00009	0.0111	3.6036
5	0.0067	0.00015	0.0224	1.7867
6	0.0011	0.00028	0.2545	0.1572
7	0.0136	0.00017	0.0125	3.2000
8	0.3585	0.08886	0.2479	0.1614
9	0.0019	0.00012	0.0632	0.6333
10	0.0178	0.00021	0.0118	3.3898
11	0.1009	0.04338	0.4299	0.0930
12	0.0023	0.00028	0.1217	0.3287
13	0.1114	0.00538	0.0483	0.8283
14	0.0653	0.00235	0.0360	1.1114
15	0.0004	0.00101	2.5250	0.0158
16	0.0004	0.00463	11.5750	0.0035
17	0.0005	0.00040	0.8000	0.0500
18	0.0005	0.00164	3.2800	0.0122
19	0.0020	0.00031	0.1550	0.2581
Mean	0.0374	0.00790	1.0496	1.1299
Std.Dev	0.0849	0.02192	2.7006	1.4394
Exp.Mean	0.0479	0.00699	1.1450	

APPENDIX M

SOLUTE TRANSPORT PARAMETERS FOR MEDIUM BT HORIZON CORES

DEPTH=Bt VOL=Med

CORE	v(m/day)	D(m^2/d)	DISP(m)	P
1	0.1747	0.00408	0.02335	2.6124
2	0.0735	0.00244	0.03320	1.7330
3	0.0525	0.00162	0.03086	1.8911
4	0.2815	0.04928	0.17506	0.3310
5	0.0652	0.00400	0.06135	0.9410
6	5.8702	1.58177	0.26946	0.2086
7	0.5483	0.15902	0.29002	0.2048
8	0.5063	0.06826	0.13482	0.4404
9	5.2634	5.98511	1.13712	0.0510
10	0.4857	0.01647	0.03391	1.6886
11	0.1323	0.00478	0.03613	1.5801
12	0.0014	0.00029	0.20714	0.2806
13	0.4250	0.00875	0.02059	2.8529
14	2.1652	0.49386	0.22809	0.2537
15	9.2164	6.43010	0.69768	0.0830
16	0.3557	0.01276	0.03587	1.6727
17	0.3173	0.03880	0.12228	0.4723
18	0.1512	0.02501	0.16541	0.3479
19	0.0407	0.00097	0.02383	2.4948
Mean	1.3741	0.78355	0.19611	1.0600
Std.Dev	2.5520	1.94770	0.27918	0.9527
Exp.Mean	2.3361	1.60720	0.19966	

APPENDIX N

SOLUTE TRANSPORT PARAMETERS FOR LARGE BT HORIZON CORES

DEPTH=Bt VOL=Large

CORE	v(m/day)	$D(m^2/d)$	DISP(m)	P
1	0.3144	0.01098	0.03492	2.6629
2	0.0342	0.00218	0.06374	1.3716
3	0.7434	0.04755	0.06396	1.4818
4	1.1912	0.81396	0.68331	0.1513
5	1.3956	0.52377	0.37530	0.2605
6	2.0147	0.31387	0.15579	0.5975
7	5.0846	2.08654	0.41036	0.2252
8	2.5727	0.92225	0.35848	0.2407
9	4.0925	4.58662	1.12074	0.0831
10	1.5507	0.44361	0.28607	0.3012
11	6.1451	1.10465	0.17976	0.5475
12	0.1434	0.05153	0.35934	0.2732
13	2.2753	0.53753	0.23625	0.4191
14	7.9928	6.00704	0.75156	0.1287
15	3.2890	1.39428	0.42392	0.2408
16	0.3962	0.17625	0.44485	0.1965
17	1.3840	0.71421	0.51605	0.1807
18	3.4356	2.11570	0.61582	0.1462
19	0.3907	0.06511	0.16665	0.5433
Mean	2.3393	1.15356	0.38141	0.5290
Std.Dev	2.2038	1.61167	0.00218	0.6462
Exp.Mean	3.3404	2.89293	0.42397	

APPENDIX O

R^2 VALUES FOR CUMULATIVE FREQUENCY DISTRIBUTIONS

		Core Size			
Parameter	Depth	Small	Medium	Large	In-Situ
lnKs	Ap	0.912	0.656	0.948	0.967
	Bt	0.945	0.947	0.837	0.822
lnv	Ap	0.923	0.705	0.908	
	Bt	0.953	0.869	0.889	
lnD	Ap	0.952	0.707	0.850	
	Bt	0.870	0.942	0.889	
lnDisp	Ap	0.762	0.831	0.961	
	Bt	0.953	0.944	0.899	

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