J. ENVIRONMENTAL SYSTEMS, Vol. 26(2) 171-189, 1997-98

DEPENDENCE OF VARIABILITY IN HYDRAULIC PROPERTIES ON PHYSICAL PROPERTIES OF FIELD SOIL*

J. Y. DIIWU

R. P. RUDRA

W. T. DICKINSON

University of Guelph, Ontario, Canada

G. J. WALL
Land Resource Research Centre, Ontario, Canada

ABSTRACT

A method based on the spatial distribution of texture and bulk density has been proposed for characterizing spatial variations in the hydraulic properties of soils. Soil samples collected from the A and B horizons of the study field were analyzed for texture, bulk density, soil water retention, and saturated hydraulic conductivity. Analysis of the data showed that these soil properties are spatially variable between the A and B horizons and between zero tillage and conventional tillage treatments. A multiple linear regression relation was developed to relate the spatial variability of soil water characteristics to the variability of texture and bulk density. The coefficients of the derived relation reveal that the influence of physical properties on variability in hydraulic characteristics of soil does not only depend on the degree of saturation of the soil, but also on horizon and tillage treatment. Soil water content predicted with the derived relation compared fairly well with observed soil water content.

*The financial support of each of the following organizations to this work is greatly appreciated: Natural Science and Engineering Research Council (NSERC) of Canada, the Canadian Commonwealth Fellowship Programme, and the Water Resources Research Institute of CSIR, Ghana.

doi: 10.2190/ECE7-2PY3-N3LH-VVKA
http://baywood.com

INTRODUCTION

Richard's equation, which is based on the integration of Darcy's law with mass balance analysis, has been the most commonly used physically-based model for studying the movement of water through soil. There are two major problems in obtaining the solution to Richard's equation. Due to high non-linearity the equation is expensive to solve; and the coefficients in the equation, soil hydraulic conductivity and specific moisture capacity, exhibit spatial and temporal variability which renders their measurement in the field expensive and time consuming [1-4].

One approach used to deal with the variability of hydraulic properties of soils has been based on the assumption that the field consists of parallel non-interacting stream tubes [5]. However, the uncertainty of an appropriate scale and the assumption that each stream tube is uniform with depth limit the application of this approach. The other approach is called the scaling approach: soil water properties are scaled according to the concept of similar media [2]. The strength of this approach is that it represents spatial variability by a single physically-based parameter. Its major weakness however, is that it is an approximate method.

Attempts to improve the stream tube and scaling theory approaches have resulted in the development of stochastic models [4-7]. There have also been attempts to quantify spatial variability of soil hydraulic properties by introducing chemical and physical factors [8]. Despite these efforts an approach is still needed which would relate the spatial variability of hydraulic properties of soil to the easily measurable physical properties. Even though a relation between soil water content and clay content, silt to clay ratio, and bulk density has been proposed, the equation does not include sand content [9]. Moreover, the inclusion of silt to clay ratio in the equation has created the possibility of eliminating the effect of the spatial distribution of silt and clay contents on soil hydraulic properties.

The transmission of water and contaminants through soil is governed by four factors: properties of the soil, hydraulic loading on the soil, properties of the contaminant being transmitted, and land management practices. Therefore, before an appropriate model can be hypothesized for the transmission of water and contaminants at a particular field site, it is necessary to ascertain the extent of spatial and temporal variability of soil properties in the field. This paper focuses on the spatial variability of hydraulic and physical properties of soil in the A and B horizons with changes in tillage.

METHODOLOGY

The data set used for this study consisted of bulk density, total porosity, texture, organic matter content, saturated hydraulic conductivity, and volumetric soil water content at matric potentials of 10, 25, 50, 100, 333, 1000, 1500, 3500, 8000, 15000 cm of water. These were determined from soil samples collected from a farm located in the Kettle Creek Watershed in southwestern Ontario, Canada. In 1989 the farm was divided into zero tillage and conventional tillage sites for management purposes, and has remained so since then. The crop rotation followed was wheat, soybean, and corn. The thickness of the A horizon in the study field varies from 25 cm to 30 cm and the portion of the B horizon considered for this study varies between 25 cm and 30 cm in thickness.

Two sets of soil cores and one set of free hand soil samples were collected from the A and B horizons at several locations at the zero tillage and conventional tillage treatment sites. Bulk density at each sampling location was determined by the gravimetric method using one set of the core samples; the other set was used to determine soil water characteristics at the listed matric potentials by using the pressure plate method [10]. The free hand samples were used to determine the soil texture and organic matter content at each sampling location. Total porosity at each sampling location was determined from the bulk density using the following relation:

$$e_t = \left[1 - \frac{\rho_b}{\rho_s}\right] 100 \qquad (1)$$

where

e_t = total porosity (%),
ρ_b = bulk density (kg/m^3), and
ρ_s = particle density (kg/m^3).

The value of 2650 kg/m^3 was used as an estimate of particle density in this study [10].

Soil water characteristics and hydraulic conductivity of field soil are being recognized to be stochastic parameters [1, 8, 11]. One approach used to analyze these parameters has been to assume the particular parameter to be lognormally distributed, and then to derive the statistical moments and their confidence limits. With this information, values of the parameter can be estimated subject to the specified confidence limits [1, 2, 11, 12]. The other approach derives a multiple regression relation, a pedo-transfer function between the soil hydraulic parameter and easily measurable soil physical parameters of sand, silt, clay, organic matter contents, and bulk density [12-15]. The established relation can then be used to estimate the hydraulic parameter. The second approach has been adopted in this study to relate the variability in soil water characteristics to soil physical properties. Multiple linear regression was used to develop a relationship between soil water content (θ) at each value of matric potential (ψ), and texture (% sand, % silt, and % clay), and bulk density (ρ_b) using SYSTAT program [16]. The relationship developed is of the form:

$$\theta_\psi = A_0 + A_1\,(\%\text{Sand}) + A_2\,(\%\text{Silt}) + A_3\,(\%\text{Clay}) + A_4\rho_b \qquad (2)$$

where

A_0 = the intercept,
A_1 = regression coefficient corresponding to % sand,
A_2 = regression coefficient corresponding to % silt,
A_3 = regression coefficient corresponding to % clay, and
A_4 = regression coefficient corresponding to bulk density.

The multiple regression coefficients, along with the coefficients of determination and the standard errors of estimate for the zero tillage and conventional tillage treatments were determined. The regression coefficients were used to describe the variability in soil water characteristics with the variability in the corresponding physical property. The goodness-of-fit of the multiple regression relations was tested by estimating soil water content from a set of physical properties using the relations, and then comparing the predicted values with an independent set of observed soil water content values.

RESULTS AND DISCUSSION

Soil Physical Properties

Physical properties of soil in the test field are presented in Table 1 and Figures 1 to 5. These data reveal the central tendency and variability of the site data by soil horizon and by tillage treatment. The mean represents a central value about which the realizations of the selected soil properties in the field are clustered. The coefficients of variation represent the spatial variability of the soil properties.

The mean sand, silt, and clay contents and the corresponding coefficients of variation shown in Table 1 were plotted on texture triangles (Figures 1 to 5), along with the individual sample points. The portion of the texture triangle containing all the sample points is shown in Figure 1, and then expanded in Figures 2 to 5. These figures reveal that the soil texture points, representing the mean sand, silt, and clay contents in both horizons for both tillage treatments, fall within the texture zone for silt loam. However, there are noticeable differences in mean particle size, between horizons and tillage treatments. Overall the spatial variability of particle size distribution over the test field is fairly high. The variability of sand, silt, and clay contents are higher in the B horizon than in the A horizon as indicated by the higher coefficients of variation. The spatial variability of clay content in the A and B horizons is also generally higher for the zero tillage treatment than for the conventional tillage treatment. Sand and clay contents seem to exhibit higher variability in the B horizon than the A horizon for the zero tillage treatment.

The differences in variability of particle size distribution between horizons and between tillage treatments are also indicated by the relative sizes of the zones of variability and the degree of cluster of the sample points in Figures 2 to 5.

Table 1. Physical Properties of Soils Used in the Study

	Zero Tillage		Conventional Tillage	
Horizon	A	B	A	B
Sand (%)	24.3-31.3 (27.92) [0.072]	12.8-30.2 (24.54) [0.329]	30.1-36.5 (32.36) [0.075]	27.5-34.3 (30.23) [0.083]
Silt (%)	51.8-55.5 (54.05) [0.023]	42.3-59.4 (52.54) [0.092]	49.9-55.6 (53.92) [0.042]	53.9-59.8 (57.45) [0.037]
Clay (%)	15.5-22.1 (18.05) [0.117]	10.4-37.1 (2292) [0.425]	13.4-14.9 (13.85) [0.040]	10.0-15.1 (12.32) [0.152]
Organic Matter Content (%)	3.5-4.3 (3.66) [0.082]	0.7-1.2 (0.94) [0.191]	2.3-3.5 (2.98) [0.140]	0.9-1.4 (1.1) [0.208]
Bulk Density (kg/m^3)	1250-1450 (1390) [0.057]	1450-1650 (1600) [0.011]	1250-1450 (1370) [0.070]	1280-1630 (1610) [0.041]
Total Porosity (%)	43.7-51.4 (45.10) [0.063]	36.5-44.8 (41.11) [0.062]	44.1-51.0 (41.25) [0.075]	38.6-39.9 (42.26) [0.017]

* - * : Range of Values
( ) : Mean Value
[ ] : Coefficient of Variation

The sample points in Figure 2 are more tightly clustered together than those in Figure 5, while the zone of variability is greater in the latter than the former. Considering the zone of variability, there was greater variability in particle size distribution in the B horizon than in the A horizon for the zero tillage treatment (Figures 2 and 3). Similarly for the conventional tillage treatment there was greater variability in particle size distribution in the B horizon than the A horizon (Figures 4 and 5). The variability in particle size distribution was greater for the zero tillage treatment than for the conventional tillage treatment. A two-sample *t* test showed that the differences in coefficients of variation are significant at the 5 percent significance level. Hence, for particle size distribution, any noticeable differences from one location to another are part of a random variability in the field.

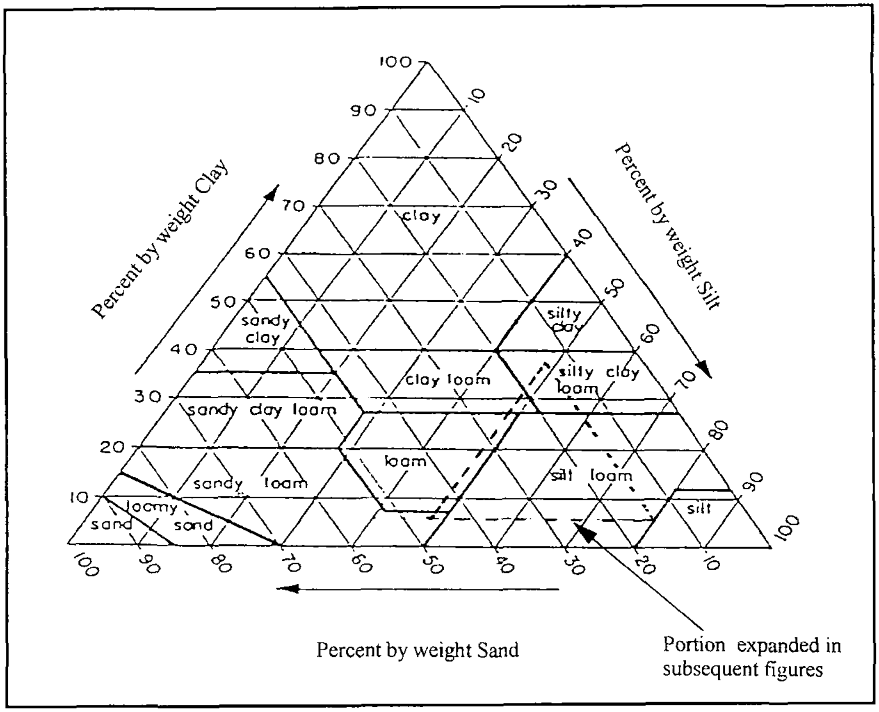

Figure 1. Texture triangle showing portion containing all the soil samples analyzed.

The summary of results presented in Table 1 reveal that bulk density in the test field varies from 1250 to 1650 kg/m^3. From these results it appears that the mean bulk density values differ from horizon to horizon, being higher for the B horizon but essentially the same from the zero tillage treatment to the conventional tillage treatment. The variability in values is a function of horizon and tillage treatment, being greater in the A horizon than in the B horizon and being greater for the conventional tillage treatment than for the zero tillage treatment. A two-sample *t* test at the 5 percent significance level confirmed that the means are significantly different between horizons but not between tillage treatments, and the variances are significantly different between horizons and between tillage treatments. The timing of sampling may be one possible cause of similar mean bulk densities between tillage treatments. Soil samples were collected in October, by which time the tilled soil had set well enough for the bulk densities of the zero tillage and conventional tillage treatments to be similar.

The results on organic matter presented in Table 1 show that in the test field this soil property varied between 0.7 and 3.5 percent. The mean organic matter

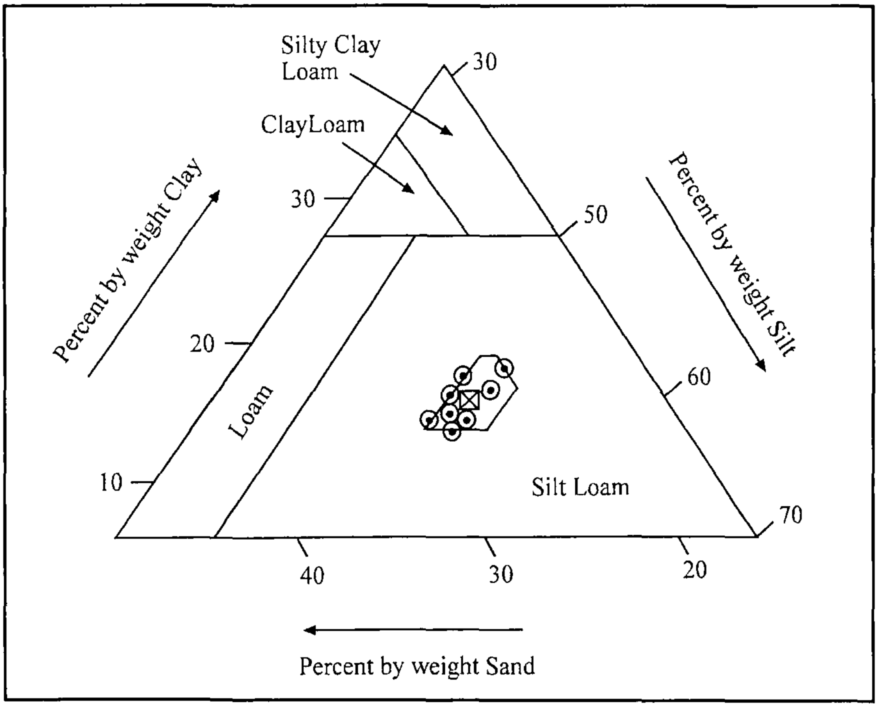

Figure 2. Zone of variability showing mean (X) and sample points of particle size distribution in A horizon for zero tillage treatment.

content is a function of both horizon as well as tillage treatment, being greater in the A horizon than in the B horizon for both tillage treatments. In the A horizon the mean organic matter content is higher for the zero tillage treatment than for the conventional tillage treatment, while this order is reversed in the B horizon. This is probably attributable to the mixing of decomposed vegetation during tillage. Such a process is likely to reduce the amount of organic matter that would have been present in the A horizon while making some of it available in the B horizon. The spatial variability of organic matter content is higher for the conventional tillage treatment than for the zero tillage treatment, being more in the A horizon than in the B horizon. Statistical analysis revealed that the means and coefficients of variation between the zero tillage and conventional tillage treatments, are significantly different at the 5 percent significance level in the A horizon but not in the B horizon.

In the A horizon lower organic matter content for the conventional tillage treatment than for the zero tillage treatment is likely to make the soil under conventional tillage treatment more susceptible to erosion. Also, under each

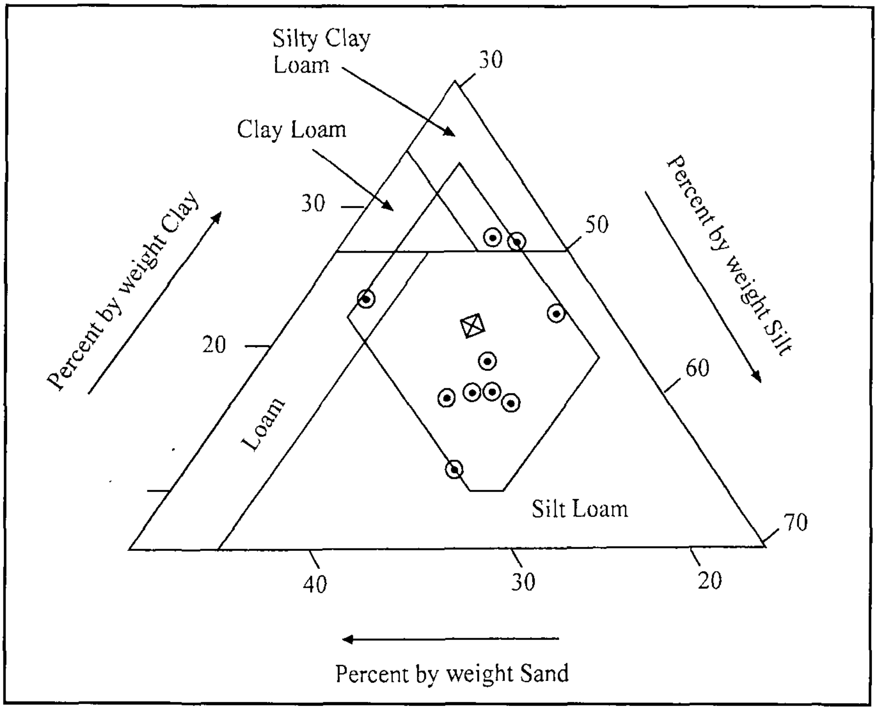

Figure 3. Zone of variability showing mean (X) and sample points of particle size distribution in B horizon for zero tillage treatment.

tillage treatment the higher organic matter content in the A horizon also provides more favorable conditions for biological activity and plant growth in this horizon, and so stable aggregates and macropores are more likely to be found in the A horizon than in the B horizon.

Total porosity of soil in the test field as revealed by results presented in Table 1 ranges from 36.5 to 51.4 percent. This soil property seems to be a function of horizon but not of tillage treatment as shown by noticeable differences between the total porosity in the A and B horizons for both tillage treatments, but only slight differences between the zero tillage and conventional tillage treatments in both the A and B horizons. A two-sample *t* test at the 5 percent significance level indicated that the mean total porosities in the A and B horizons for each tillage treatment are significantly different, but not so between treatments in each soil horizon. The variability in total porosity is the same in the two horizons for the zero tillage treatment, but slightly different for the conventional tillage treatment where it is higher in the A horizon than in the B horizon.

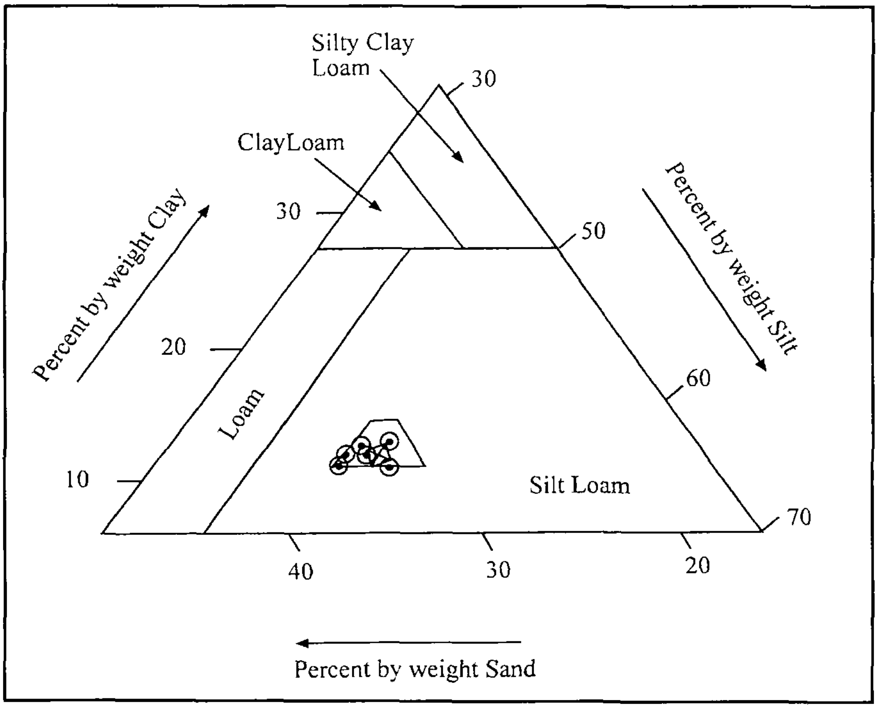

Figure 4. Zone of variability showing mean (X) and sample points of particle size distribution in A horizon for conventional tillage treatment.

Soil Hydraulic Properties

Saturated hydraulic conductivity and soil water characteristics are the two soil hydraulic properties analyzed for the test field. The measured soil water characteristics for the zero tillage and conventional tillage treatments are presented in Table 2. The water retention capacity of soil has been described by the amount of gravity water and capillary water. The gravity water was determined by taking the difference between water content at saturation and that at field capacity. The capillary water has been computed by taking the difference between water content at field capacity and permanent wilting point. Water content at field capacity and permanent wilting point correspond to matric potentials of 333 cm and 15000 cm of water, respectively. These data show that for both tillage treatments gravity water is more in the A horizon than in the B horizon. The gravity water depends on total porosity. In this case as explained earlier the total porosity of the A horizon was greater than that of the B horizon. Greater amount of organic matter resulted in better degree of aggregation in the A horizon for both tillage treatments.

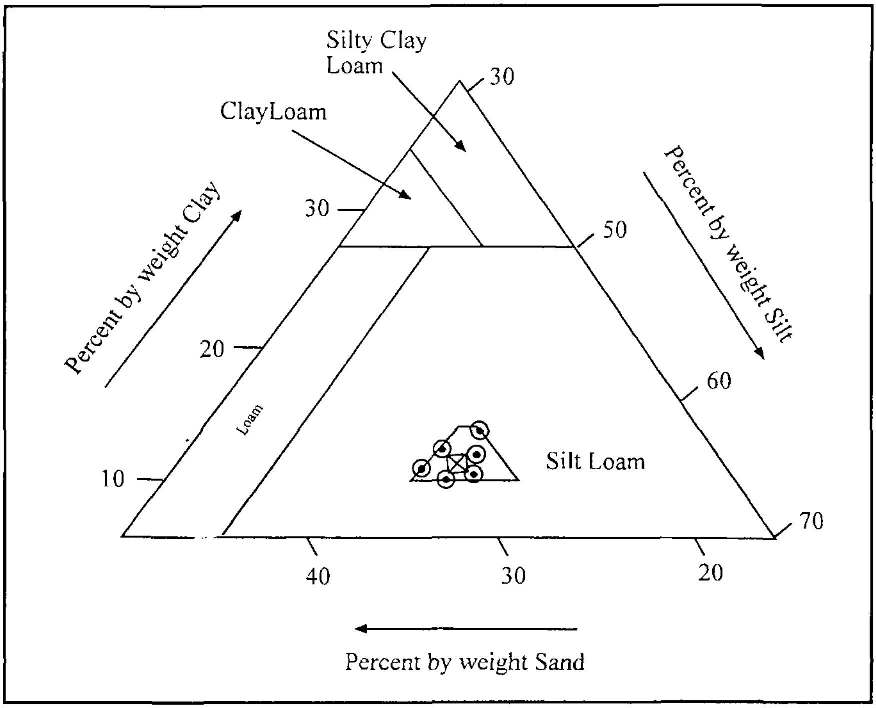

Figure 5. Zone of variability showing mean (X) and sample points of particle size distribution in B horizon for conventional tillage treatment.

Table 2. Distribution of Soil Water Characteristics in the Field

Matric Potential (cm of Water)	Soil Water Content (cm^3/cm^3)			
	Zero Tillage		Conventional Tillage	
	A Horizon	B Horizon	A Horizon	B Horizon
10	0.449	0.410	0.414	0.417
100	0.329	0.292	0.344	0.283
333	0.281	0.277	0.274	0.257
1000	0.259	0.255	0.244	0.213
1500	0.245	0.232	0.225	0.186
3500	0.231	0.211	0.209	0.158
8000	0.209	0.186	0.182	0.123
15000	0.199	0.167	0.169	0.100

The capillary water did not show any trend between A and B horizons. In this case for zero tillage treatment there is more capillary water in B horizon than in the A horizon, while the trend is reversed for conventional tillage treatment. For this tillage treatment the water content at field capacity between the A and B horizons was very similar. This may be due to similar degree of aggregation, which depends upon the combined effect of organic matter and clay content. The effect of more organic matter in the A horizon was probably neutralized by low clay content.

Saturated hydraulic conductivity was determined using the constant head permeameter method [17] and its spatial variability was analyzed. Table 3 summarizes values of saturated hydraulic conductivity by horizon and tillage treatment. The mean saturated hydraulic conductivity in the A and B horizons for the conventional tillage treatment are significantly different at the 5 percent significance level, but not for the zero tillage treatment.

In each horizon the mean saturated hydraulic conductivity for the zero tillage treatment is significantly different from that for the conventional tillage treatment. The range of values of saturated hydraulic conductivity is high and is a function of horizon and tillage, being greater for the zero tillage treatment than for the conventional tillage treatment. For the zero tillage treatment the range is higher in the A horizon than in the B horizon, while for the conventional tillage treatment it is higher in the B horizon than in the A horizon. The variability of saturated hydraulic conductivity seems to be a function of horizon as well as tillage, being greater for the zero tillage treatment than for the conventional tillage treatment. The variability of this soil property is also greater in the A horizon than in the B horizon for the zero tillage treatment, and in the B horizon than in the A horizon for the conventional tillage treatment.

Tillage tends to modify the bulk density and hence total porosity and pore size distribution of soil, and so it is expected that saturated hydraulic conductivity would be correspondingly affected. The higher mean saturated hydraulic

Table 3. Distribution of Saturated Hydraulic Conductivity (cm/hr) in the Field

Zero Tillage		Conventional Tillage	
A Horizon	B Horizon	A Horizon	B Horizon
0.929-50.753 (9.745) [1.403]	1.210-37.296 (9.134) [1.198]	1.012-6.530 (3.341) [0.684]	0.731-14.242 (5.839) [0.850]

* - * : Range of Values
( ) : Mean Value
[ ] : Coefficient of Variation
Depth of plough layer: 25 cm

conductivity for the zero tillage treatment than for the conventional tillage treatment may be partly attributed to the effect of tillage, since undisturbed macropores for the zero tillage treatment provide channels for the transmission of water. The other probable cause of these higher mean values is that tillage tends to alter the pore size distribution of soil, especially in the large and small size ranges.

The greater variability of saturated hydraulic conductivity in the A horizon than in the B horizon for the zero tillage treatment may be attributed to the greater likelihood of the occurrence of aggregates in the former than in the latter horizon which could be a result of the higher organic matter content in the A horizon. In the case for the conventional tillage treatment the higher variability of saturated hydraulic conductivity in the B horizon than in the A horizon is probably due to non-uniform compaction under the plough layer in the B horizon during tillage. Since some aggregates are destroyed in both the A and B horizons for the conventional tillage treatment during tillage, aggregates are more likely to occur in both horizons for the zero tillage treatment than for the conventional tillage treatment. This probably caused the higher variability of saturated hydraulic conductivity for the zero tillage treatment than for the conventional tillage treatment.

The ranges and coefficients of variation values of saturated hydraulic conductivity are much higher than those of the other soil properties analyzed in this study. This reveals that saturated hydraulic conductivity is the most variable of all the soil properties in the field. However, further studies would be needed to be able to explain the possible causes of the greater variability of saturated hydraulic conductivity than the variabilities of other soil properties in the field.

Relating Variability in Hydraulic Properties to Physical Properties of Soil

Correlation coefficients between saturated hydraulic conductivity and the other soil water properties were computed and presented in Table 4. Since all the correlation coefficients are non-zero this indicates the existence of a relationship between the physical and hydraulic properties of soil. However, the correlations are a function of horizon and tillage treatment. They are all significant except for bulk density in the A horizon as well as for bulk density, sand and clay contents in the B horizon for the tillage treatment. For the conventional tillage treatment the correlation coefficients are significant except for silt content and effective porosity in the A horizon, and silt and organic matter content in the B horizon. The results indicate that saturated hydraulic conductivity is not highly correlated with bulk density for the zero tillage treatment probably because the effect of macroporosity and aggregation on this soil hydraulic property tends to be greater than that of bulk density. Also saturated hydraulic conductivity is not highly correlated with silt content but fairly highly correlated with bulk density for the conventional tillage treatment.

Table 4. Correlation Coefficients of Saturated Hydraulic Conductivity with Bulk Density, % Sand, % Silt, % Clay, % Organic Matter, and Effective Porosity

	Zero Tillage		Conventional Tillage	
	A Horizon	B Horizon	A Horizon	B Horizon
Bulk Density	−0.120*	−0.132*	−0.443	−0.443
% Sand	0.552	0.029*	0.319	0.486
% Silt	0.500	−0.406	−0.015*	−0.143*
% Clay	−0.971	0.145*	0.339	−0.371
% OrgM**	0.493	−0.224	−0.235	0.029*
Effective Porosity	0.252	0.347	0.048*	0.347

*Not significant
**OrgM: Organic Matter Content

Regression relations of the form of equation 2 were developed by taking soil water content at various matric potentials as criterion variable, while sand, silt, and clay contents and bulk density were taken as the predictor variables. Total porosity was not used for the regression since that could have resulted in multicollinearity due to correlation between this soil property and the other soil physical properties.

The data for the A and B horizons were pooled for each of the zero tillage and conventional tillage treatments. The physical properties of soil in each horizon incorporate the effects of solutes, swelling and shrinking of clay, development of soil from parent material, and land management factors on that horizon. Hence the pooled data would incorporate the effects of all these factors in the A and B horizons. Since variability in soil hydraulic properties is partly due to these effects, it is expected that the regression coefficients obtained would account for such variability. Moreover, along with analytical expressions for soil water characteristics, it should be possible to adequately describe soil water flow in the field with limited information. The multiple regression coefficients, along with the coefficients of determination and the standard errors of estimate for the zero tillage and conventional tillage treatments are shown in Tables 5 and 6.

The regression coefficients presented indicate the degree of impact of variability of the physical properties on variability of soil water characteristics in the field. The regression coefficients corresponding to bulk density for the zero tillage treatment are very low compared to those corresponding to the other soil physical properties for that tillage treatment. The regression coefficients corresponding to sand, silt, and clay contents probably indicate that in the field the variability of clay content would have a slightly greater effect on soil water characteristics than those of sand and silt contents. For the conventional tillage

Table 5. Coefficients of Multiple Regression as Used in Equation 2 for the Zero Tillage Treatment

Matric Potential (cm)	A_0	A_1	A_2	A_3	A_4	R^2	SEE
10	−33.52	0.339	0.341	0.34	−0.038	0.873	0.048
100	−58.55	0.587	0.59	0.59	−0.035	0.857	0.042
333	−21.29	0.213	0.216	0.217	0.021	0.948	0.025
1000	−17.47	0.176	0.176	0.18	0.011	0.955	0.027
1500	−18.93	0.191	0.192	0.196	−0.042	0.957	0.028
3500	−18.01	0.182	0.183	0.187	−0.072	0.965	0.031
8000	−18.67	0.189	0.189	0.194	−0.094	0.959	0.032
15000	−21.65	0.22	0.219	0.225	−0.132	0.963	0.033

Table 6. Coefficients of Multiple Regression as Used in Equation 2 for the Conventional Tillage Treatment

Matric Potential (cm)	A_0	A_1	A_2	A_3	A_4	R^2	SEE
10	3.664	−0.032	−0.032	−0.034	−0.01	0.992	0.055
100	2.419	−0.018	−0.021	−0.01	−0.17	0.821	0.033
333	2.766	−0.023	−0.03	−0.016	0.076	0.933	0.037
1000	3.941	−0.033	−0.044	−0.023	0.037	0.973	0.012
1500	4.913	−0.04	−0.055	−0.033	0.024	0.977	0.013
3500	4.843	−0.038	−0.054	−0.033	0.001	0.965	0.018
8000	4.844	−0.039	−0.054	−0.032	−0.025	0.885	0.034
15000	5.136	−0.043	−0.056	−0.033	−0.073	0.883	0.035

treatment the impact of variability of bulk density on soil water characteristics would be the same as that of the variability of each of the other physical properties as indicated by the low regression coefficients for all the soil properties considered. The regression coefficients probably also indicate that the soil physical properties considered would influence soil water characteristics more at low matric potentials than at high ones.

The high coefficient of determination (R^2) values indicate that the multiple regression relations are statistically good, these being even better as the soil degree of saturation decreases for the zero tillage treatment and as the degree of saturation increases for the conventional tillage treatment. The relations are at least 95 percent reliable as indicated by the low standard error of estimate (SEE) values, but there is no clear trend in this with respect to matric potential.

The goodness-of-fit of the multiple regression relations were further illustrated by predicting soil water content using the fitted multiple regression equations, and then comparing them with some observed independent set of soil water content valuese at the corresponding matric potentials. There was quite good agreement between predicted and observed soil water contents in both the A and B horizons for the zero tillage and conventional tillage treatments, as illustrated by the approximation to the 1:1 line in Figures 6 to 9. Hence the proposed relation performs quite well.

CONCLUSIONS

The analysis of soil physical properties of particle size distribution, organic matter content, bulk density, and total porosity showed that each of these soil properties varies in the field. The saturated hydraulic conductivity and soil water characteristics were also found to be variable within each horizon, between the zero tillage and conventional tillage treatments, and between the A and B horizons for each tillage treatment. Non-uniform distribution of organic matter

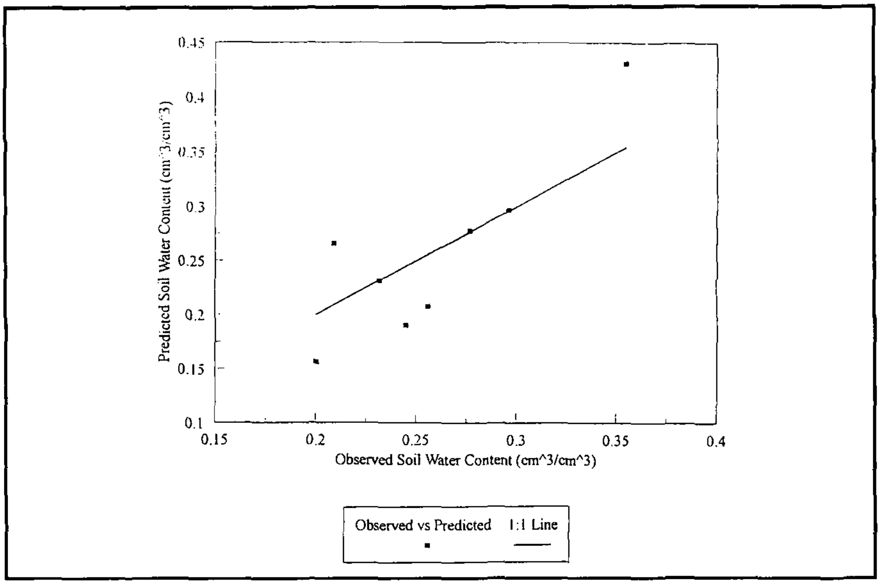

Figure 6. Comparison of observed and predicted soil water content using multiple regression relation in A horizon for zero tillage treatment.

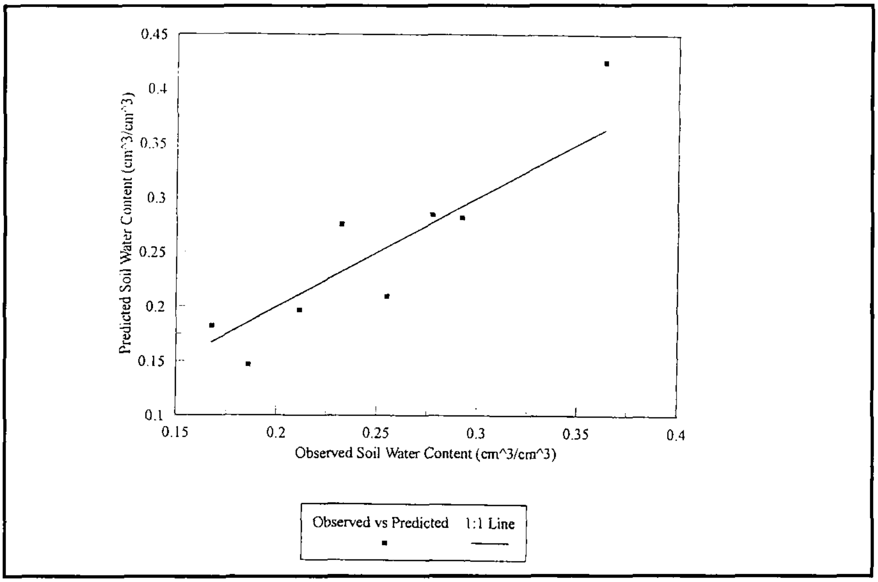

Figure 7. Comparison of observed and predicted soil water content using multiple regression relation in B horizon for zero tillage treatment.

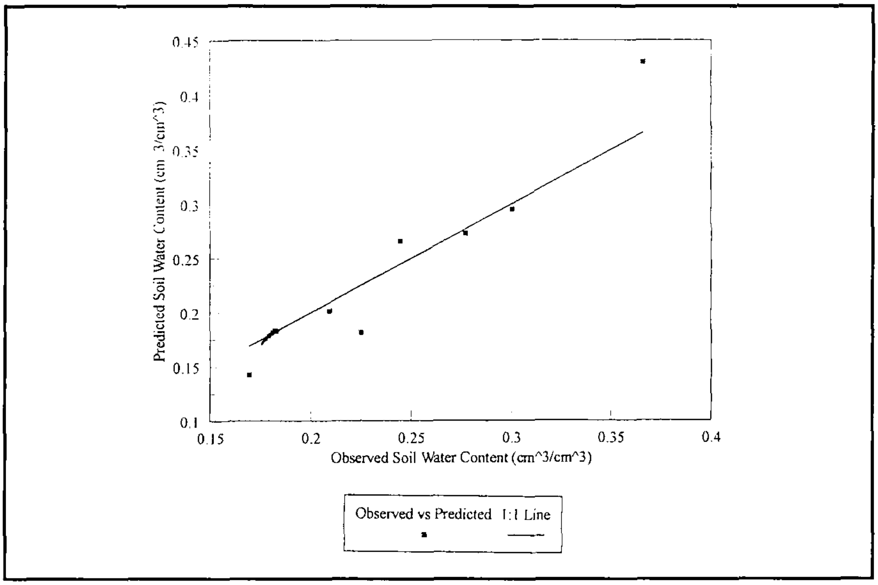

Figure 8. Comparison of observed and predicted soil water content using multiple regression relation in A horizon for conventional tillage treatment.

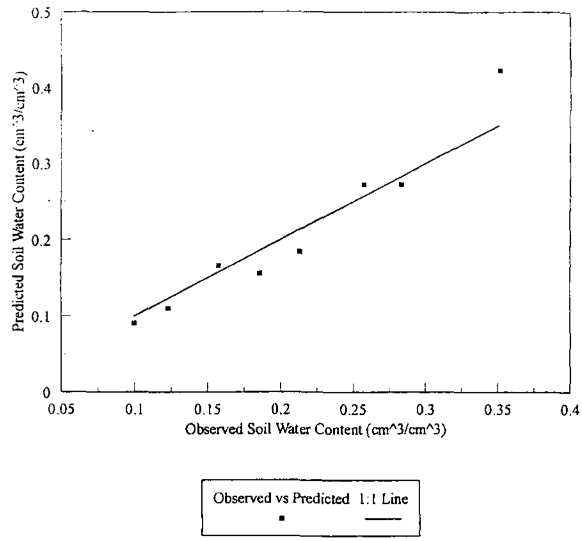

Figure 9. Comparison of observed and predicted soil water content using multiple regression relation in B horizon for conventional tillage treatment.

content in the field is one probable cause of the variability of bulk density. The spatial distribution of structural voids such as macropores as well as aggregation in the field soil are other probable causes of the variability of the physical and hydraulic properties.

The variability of saturated hydraulic conductivity may be partly attributed to spatially distributed macropores and aggregates in the field. It may also be attributed to the fact that tillage tends to alter pore size distribution, especially in the large and small size ranges. Hence the spatial distribution of the transmission of water in the field is correspondingly affected. The coefficient of variation values of saturated hydraulic conductivity are between 70 percent and 140 percent as compared to 1 percent to 40 percent for all the physical properties, indicating that saturated hydraulic conductivity is likely to be the most variable soil property in the test field. However, the physical properties have influence on the hydraulic properties directly or indirectly, as indicated by the correlation coefficients between them.

The derived multiple regression relation between soil water characteristics and physical properties of field soil has been found to perform quite well. The regression coefficients indicate that the impact of any of the physical properties on the variability in soil hydraulic properties depends on horizon and tillage treatment. The coefficients also reveal that the physical properties would influence variability in soil hydraulic properties more as the degree of saturation of the soil increases than as it decreases.

REFERENCES

1. D. R. Nielsen, J. W. Bigger, and K. T. Erh, Spatial Variability of Field-Measured Soilwater Properties, *Hilgardia, 42*, pp. 215-259, 1973
2. A. J. Peck, R. J. Luxmore and J. L. Stolzy, Effects of Spatial Variability of Soil Hydraulic Properties in Water Budget Modelling, *Water Resources Research, 13*, pp. 348-354, 1977.
3. L. R. Ahuja, J. D. Ross, R. R. Bruce, and D. K. Cassel, Determining Unsaturated Hydraulic Conductivity from Tensiometric Data Alone, *Soil Science Society of America Journal, 52*, pp. 27-34, 1988.
4. J. Y. Diiwu, *Transfer Function Modelling of Drainage and Solute Transport through Layered Macroporous Soil*, Ph.D. thesis, School of Engineering, University of Guelph, Guelph, Ontario, 1997.
5. G. Dagan and E. Bresler, Solute Dispersion in Unsaturated Heterogeneous Soil at Field Scale. 1. Theory. *Soil Science Society of America Journal, 43*, pp. 461-467, 1979.
6. C. S. Simmons, A Stochastic Convective Transport Representation of Dispersion in One-Dimensional Porous Media Systems, *Water Resources Research, 18*, pp. 1193-1214, 1982.
7. W. A. Jury, Simulation of Solute Transport with a Transfer Function Model, *Water Resources Research, 18*, pp. 363-368, 1982.
8. E. Bresler, G. Dagan, R. J. Wagenet, and A. Laufer, Statistical Analysis of Salinity and Texture Effects on Spatial Variability of Soil Hydraulic Conductivity, *Soil Science Society of America Journal, 48*, pp. 16-25, 1984.
9. J. L. Hutson and A. Cass, A Retentivity Function for Use in Soil Water Simulation Models, *Journal of Soil Science, 38*, pp. 105-113, 1987.
10. D. Hillel, *Fundamentals of Soil Physics,* Academic Press, Inc., San Diego, California, 413 pp., 1980.
11. A. Mantoglou and L. W. Gelhar, Stochastic Modelling of Large Transient Unsaturated Flow Systems, *Water Resources Research, 23*, pp. 57-67, 1987.
12. O. Tietje and V. Hennings, Accuracy of Saturated Hydraulic Conductivity Prediction of Pedo-Transfer Functions Compared to the Variability within FAO Textural Classes, *Geoderma, 69*, pp. 71-84, 1996.
13. G. S. Campbell, A Simple Method for Determining Unsaturated Conductivity from Moisture Retention Data, *Journal of Soil Science, 117*:6, pp. 311-314, 1974.
14. K. E. Saxton, W. J. Rawls, J. S. Romberger, and R. I. Papendick, Estimating Generalized Soil Water Characteristics from Texture, *Soil Science Society of America Journal, 50*, pp. 1031-1036, 1986.
15. J. S. C. Mbagwu, Saturated Hydraulic Conductivity in Relation to Physical Properties of Soils in the Nsuka Plains, Southeastern Nigeria, *Geoderma, 68*, pp. 51-66, 1996.
16. L. Wilkinson, M. A. Hill, J. P. Welna, and G. K. Birkenbeuel, *SYSTAT for Windows: Statistics*, Version 5.2 Edition, Evanston, Illinois, SYSTAT, Inc., 724 pp., 1992.

17. A. Klute, Laboratory Measurement of Hydraulic Conductivity of Saturated Soil, in *Methods of Soil Analysis, Part 1*, American Society of Agronomy No. 9 in Agronomy Series, C. A. Black (ed.), pp. 210-221, 1965.

Direct reprint requests to:

Dr. J. Y. Diiwu
14 Mohawk Drive
Guelph, Ontario, Canada N1E 1J1