Impact of organic waste amendments on soil hydraulic properties and on water partitioning¹

Adrian Unc and Michael J. Goss

Abstract: Land application of organic wastes can lead to contamination of ground- and surface waters. The pathway taken by particulate contaminants, such as microorganisms, is entirely dependent on the partitioning of the incoming rain or irrigation water. The soil hydraulic properties are critical in determining the infiltration:runoff water-partitioning ratio. Components of the land applied organic waste can modify the soil hydraulic properties and thus alter this ratio. It was shown that liquid manure impacted matrix and macropore flow differently; favouring the later through obstruction of the former. In contrast solid manure favoured matrix flow over macropore flow thereby increasing the water storage in soil, which tended to reduce the likelihood of runoff. The relationships between soil hydraulic conductivity and soil textural and structural properties in repacked soil columns was unrelated to the relationships obtained for the same soils maintained in their natural undisturbed field state.

Key words: organic waste, manure, soil type, hydraulic conductivity, water partitioning, transport, contaminants.

Résumé : Le dépôt de déchets organiques sur le sol peut mener à la contamination des eaux de surface et souterraines. Le chemin pris par les contaminants particuliers, tels que les micro-organismes, dépend entièrement du partage des eaux de pluie et d'irrigation. Les propriétés hydrauliques du sol déterminent essentiellement le rapport de partage infiltration:ruissellement de l'eau. Les composantes des déchets organiques déposés sur le sol peuvent modifier les propriétés hydrauliques du sol et, ainsi, affecter ce rapport. Il a été démontré que le fumier/lisier liquide a un impact différent sur l'écoulement à travers la matrice et les micropores, favorisant ces dernières par l'obstruction de la matrice. À l'opposé, le fumier/lisier solide favorise l'écoulement à travers la matrice par rapport à celui dans les macropores, augmentant ainsi le stockage de l'eau dans le sol, ce qui tend à réduire la probabilité de ruissellement. Les relations entre la conductivité hydraulique du sol et les propriétés texturales et structurales du sol dans des colonnes de sol recomposé n'étaient pas reliées aux relations obtenues pour les mêmes sols maintenus dans leur état naturel non perturbé sur le terrain.

Mots clés : déchets organiques, fumier, lisier, type de sol, conductivité hydraulique, partage des eaux, transport, contaminants.

[Traduit par la Rédaction]

Introduction

The Walkerton tragedy of 2000 (O'Connor 2002) highlighted the potential for bacterial pathogens from manure to contaminate drinking water resources. Both stored manure and manure land applied to provide nutrients to subsequent crops represent threats to these resources. The potential for bacteria from land-applied manure to contaminate ground and surface waters

depends largely on the pathway taken by the precipitation or irrigation water in which they are suspended. Water at the soil surface can infiltrate into the soil profile or flow overland into adjacent fields or surface water bodies. Infiltrating water can carry enteric bacteria from manure through the soil (Unc and Goss 2003). It is also known that manure can result in bacteria being present in the runoff from cropland (Patni et al. 1985). Soil hydraulic properties are important in the partitioning of water into infiltration and runoff. Infiltrability of a soil determines the maximum rate at which rain or irrigation water can enter a soil. As soon as the rain or irrigation rates rise above the infiltrability (infiltration rate) dictated by the soil properties, ponding, macropore flow, and surface runoff can occur (McCoy et al. 1994).

The soil hydraulic conductivity parameter effectively expresses the capacity of a soil to transmit water to depth in the profile. Movement of water through soil can be separated into two stages: entry of water in soil (infiltration) and the flow of water through soil (percolation). Entry of water into soil is often governed by the formation of a surface seal that follows the disintegration of soil surface aggregates and depends on the rain impact force and soil textural and structural properties (Betzalet

Received 1 December 2004. Revision accepted 14 June 2005. Published on the NRC Research Press Web site at <http://jees.nrc.ca/> on 10 May 2006.

A. Unc^{2,3} and M.J. Goss. Land and Water Stewardship, Richards Building, University of Guelph, ON N1G 2W1, Canada.

Written discussion of this article is welcomed and will be received by the Editor until 30 September 2006.

¹This article is one of a selection of papers published in this Special Issue on Biosolids.

²Present Address: Centre for Research on Environmental Microbiology, University of Ottawa, 451 Smyth Rd., Ottawa, ON K1H 8M5, Canada.

³Corresponding author (e-mail: aunc@uottawa.ca).

et al. 1997; Keren 1990; Shainberg and Singer 1988). For all practical purposes it has been found that infiltration through a surface seal is independent of the saturation state of the underlying soil matrix (Morin et al. 1981). Any management practice that affects soil structural stability is liable to have an impact on the ability of the soil to withstand the slaking and dispersion action of rainfall, and consequently affect the likelihood of seal formation and the movement of water below the surface layers.

Information in the literature about the impact of manure on the hydraulic properties of soil is scarce and circumstantial. Manure is a complex mixture of ionic and molecular, soluble and particulate, inorganic and organic compounds. Long-term application of manure is known to improve soil structure by increasing the organic matter content (Gerzabek et al. 1995) and hence improves infiltration rates. Application of manure to soil can modify the structure of the soil surface aggregates forming a soil–manure filtration pad (Barrington and Jutras 1983). The addition of salts to soil can increase clay dispersion, particularly when the hydrated ions are located in between clay platelets (Shainberg and Singer 1988). The liquid phase of manure contains significant amounts of salt (Eneji et al. 2001; Sweeten 1998) and land application can add free ions to the soil (Chang et al. 1991; Haynes and Naidu 1998). Nevertheless the impact of manure type on soil aggregate dispersion is not known.

Limited specific information is available on the immediate impact of manure on soil hydraulic properties following manure application. This knowledge is required to improve the understanding of the impact of manure properties on the partitioning of precipitation into infiltration and surface run-off, and on the infiltration of water into soil. An understanding of the significance of flow in macropores following the land application of organic waste is essential as these constitute the infiltration pathways that allow fast transport of microbial contaminants.

The objective of this study was to investigate the impact of manure type on soil transport properties and on water partitioning following manure application to soils.

The potential for manure to modify the saturated hydraulic conductivity of soils, and therefore to modify water partitioning was determined in the laboratory and was also evaluated for field measurements obtained in a related study (Unc and Goss 2003).

Methodology

Laboratory tests

Saturated hydraulic conductivity (K_{sat}) measurements

Undisturbed cylindrical soil columns of 5 cm in diameter and 5 cm in length were collected from the surface of cropped fields at three sites in Southern Ontario (Table 1). The soils were routinely tilled for crop production, but none had been disturbed in the 3 months before sampling. Macropores in these cores were therefore expected to be those associated with inter-ped spaces and root growth, but not large diameter burrows created by earthworms. The bulk density of the undisturbed soils were

$1.11 \pm 0.04 \text{ g cm}^{-3}$ for the silt loam, $1.25 \pm 0.03 \text{ g cm}^{-3}$ for the silty clay soil, and $1.35 \pm 0.03 \text{ g cm}^{-3}$ for the sandy loam. Cylinders of the same size were packed with sieved soil collected from the same three locations. The collected soil, was sieved through a 2 mm sieve, added in layers to the cylindrical columns, and compacted to a common bulk density for all three soils (1.21 g cm^{-3}). However, the sandy loam soil collapsed when wetted so that its final bulk density increased (1.38 g cm^{-3}) while the silty clay soil swelled after wetting and hence its final bulk density decreased (1.06 g cm^{-3}). The bottom of the soil columns was covered with a double layer of cheesecloth to avoid soil loss while allowing unhindered water passage, and the columns were saturated from the bottom by gradual immersion in water at 4°C over a period of 24 h. The water temperature was selected to limit the formation of gas bubbles resulting from biological activity within the soil pores. Following saturation, manure was applied on the surface of the soil columns. Two manure types were used (Table 1). The rate of manure application was adjusted to an equivalent application of 50 t ha^{-1} . Columns with no manure application were used as the control treatment. Eight repetitions were carried out for each combination of soil type, soil disturbance status (undisturbed or repacked), and manure. Manure was left on the soil surface for about 10 min until the liquid manure infiltrated in the soil. The K_{sat} of the solid beef cattle manure was also tested on columns filled with 25 g of fresh manure. Saturated hydraulic conductivity was measured with the falling head permeameter method (Reynolds 1993).

Estimation of the van Genuchten's water release curve shape factors α and n (VG_α and VG_n)

Characterization of the soil pore system was obtained from water release curves. Undisturbed and repacked soil columns from the same three soils were saturated, and their water release curves obtained by means of the pressure plate test (Topp et al. 1993). From saturation soils were equilibrated at matric potentials of -2.1 kPa , -4.1 kPa , -6.1 kPa , -7.9 kPa , -10.1 kPa , -500 kPa , -1000 kPa , and -1500 kPa and at each equilibrium stage the gravimetric moisture content was determined by weight. These columns were not treated with manure to avoid the impact of the decomposing organic material on the measurements. The closed form of van Genuchten's equation for the soil water content was fitted to the experimental results from the soil water release curves (van Genuchten 1980).

$$[1] \quad \theta(h) = \theta_r + (\theta_s - \theta_r) \times [1 + (\alpha \times \psi)^n]^{(1-n)/n}$$

where $\theta(h)$ is the volumetric soil water content ($\text{m}^3 \text{ m}^{-3}$); θ_r is the residual water content ($\text{m}^3 \text{ m}^{-3}$); θ_s is the saturation water content ($\text{m}^3 \text{ m}^{-3}$); ψ is the hydraulic pressure head (m); and α (m^{-1}) and n (unitless) are the fitted parameters.

For each soil column the measured soil water content at a potential of 1.5 MPa was used as θ_r . Thereby the two water release curves shape parameters, VG_α and VG_n , were obtained for each soil column by best fit of eq. [1] to the measured water release

Table 1. Soil and manure used in the laboratory estimations of saturated hydraulic conductivity (K_{sat}).

Soil types	Texture (% by weight)			OM (% by weight)	Particle density (g cm^{-3})	CEC ($\text{cmol}^+ \text{kg}^{-1}$)	pH
	Soil ID	Sand	Silt	Clay			
Fox sandy loam		63	29	8	2.2	2.60±0.02	12.98
Conestogo silt loam		30	50	20	4.8	2.55±0.05	27.19
Haldimand silty clay		11	48	41	5.6	2.53±0.04	28.54
Manure types							
Manure				Dry matter content (%)			
Liquid swine manure				0.5			
Solid beef cattle manure				19.3			
Control (no manure)				0			

Note: OM, organic matter; CEC, cation exchange capacity.

Table 2. Estimated van Genuchten α and n coefficients.

van Genuchten coefficients	Soil type					
	Fox sandy loam		Conestogo silt loam		Haldimand silty clay	
	repacked	undisturbed	repacked	undisturbed	repacked	undisturbed
VG_α	1.694 (0.654)*	0.108 (0.038)	0.063 (0.008)	0.165 (0.052)	0.020 (0.005)	0.018 (0.002)
VG_n	1.047	1.444	1.314	1.174	1.582	1.037

*means and standard error of means.

curve (Table 2). The curve fitting procedure was performed using a solve block within MathCAD™ software (MathSoft Engineering and Education, Inc. 1998). The procedure was initialized by giving guess values to the VG_α and VG_n and repeatedly fitting eq. [1] for each point of measurement along the matric potential curve.

These shape factors (VG_α and VG_n) change with the variation of the soil water retention curve within the range of active soil porosity. Therefore they can also be used as indirect indicators of the pore size distribution, air entry value, and hence K_{sat} (Mace et al. 1998; Blum et al. 2001). Saturated hydraulic conductivity increases with VG_n and decreases with the VG_α coefficient.

Measurement of soil particle density

The particle density was measured for each soil using the method described by Blake (1965) and Blake and Hartge (1986) on ten 10 g samples for each soil type (Table 1).

Estimation of the pore size distribution in the soil columns

By using the capillary suction equation and the total volume of water released for each drop in the water potential, the volumetric pore size distribution was obtained. This method is applicable for suctions greater than 0 (Hillel 1998). However, estimation of the volume of pores as the water potential approaches zero is rather inexact, as this approach would not identify the larger, free-draining pores in which the water potential is less than the air entry potential. Therefore the volume of the pores that drain with a suction of less than 2 kPa, which encompasses the free-draining porosity, was estimated from the total soil porosity measurements (Blake and Hartge 1986). The measured particle densities were used for the calculations.

The volume of water lost during the pressure plate test plus the residual volume left in the column at the end of the tests were deducted from the total soil porosity. The difference was considered to represent the porosity equivalent to the potential greater than -2 kPa, i.e., the largest soil pores. The water potential required to drain these pores is zero or very close to zero. The lower limit of the equivalent radius of these pores is about 50 μm .

Field assessment

The infiltration below the first 30 cm of soil and the surface runoff measurements obtained in a previous field experiment (Unc and Goss 2003) have been used to evaluate the significance of the surface application of 50 t ha^{-1} of liquid swine manure or solid beef cattle manure on the infiltration of subsequent irrigation water. Infiltration rates were estimated from volumetric water content measurements at 6 h, 12 h, and 20 h following 2 h of irrigation with a total of about 50 mm of water. The experiment was carried out on two soils: a silt loam and a sandy loam. The initial soil water content varied according to the weather conditions prior to testing.

Data analysis

The laboratory experiment was designed as a randomized block with soil type, soil disturbance status, and manure type as factors. Simple correlation was used to evaluate the potential role of the considered factors in determining the K_{sat} . The predictive potential for bacterial retention has been evaluated for all measured characteristics of the soil (% silt, % sand, % clay, % porosity, bulk density), and organic waste (dry matter content) and the estimated soil pore related parameters (VG_α and VG_n). Since some of these characteristics tend to be correlated

Fig. 1. Interquartile plot of the measured saturated hydraulic conductivity (K_{sat}). $N = 8$ for each combination of soil type – soil disturbance status – manure type. □ Median; * Outlier (values between 1.5 and 3 times away from the middle 50% of the data).

(multicollinearity), a nonlinear iterative partial least squares regression procedure (PLS) was used for this evaluation. The PLS reduces the number of predictors by extracting uncorrelated components based on the covariance between the predictor and response variables. This procedure is similar to a principal component analysis, and it can be used to analyse data with large number of predictors and a limited number of data points (Minitab 2004). The PLS components that best predicted the response variable (K_{sat}) were selected by cross-validating the fitted potential models on all the subsets obtained from the initial set of observations by leaving out one observation at a time. All statistical tests were performed using the statistical package Minitab 14®.

Results

The hydraulic conductivity was measured on saturated soil columns (K_{sat}). Therefore, the hydraulic head potential was only dependent on the depth of the ponding water on top of the soil columns, and this was taken into account in the K_{sat} calculations. If a crust formed at the soil surfaces, its hydraulic resistance was expected to govern the flux through the columns in an inverse relationship (Hillel 1998).

Significance of soil type for the measured K_{sat}

Among the undisturbed columns the silt loam columns had the largest K_{sat} , but there were no significant differences between the K_{sat} of the sandy loam and the silty clay soils (Fig. 1). With the exception of the sandy loam soil, K_{sat} was significantly reduced in the repacked columns compared to the undisturbed soil columns (Fig. 1). The lack of any effect in the sandy loam may be attributed to the poor structural stability of this soil, which tended to collapse when wetted. Hence the influence of the structural pores was much less than in the other two soils,

Fig. 2. Cumulative soil porosity distribution for the undisturbed soil columns. Soil porosity distribution has been estimated from the water release curves obtained through pressure plate tests (Topp et al. 1993).

both of which maintained their structure when wetted, despite of the fact that the sandy loam had the greatest volume of large pores (Fig. 2).

There was little difference between the K_{sat} values for repacked sandy loam and repacked silt loam, while the silty clay produced the smallest values for K_{sat} measured during the testing.

Comparison of the K_{sat} in the undisturbed soil columns indicated that the Conestogo silt loam resulted in the fastest flow. The smallest K_{sat} values were again measured in undisturbed silt clay columns; however, these values were not significantly different from those for the undisturbed sandy loam columns (Fig. 1).

Significance of manure type for the measured K_{sat}

Surface placement of the solid manure from beef cattle reduced K_{sat} significantly, relative to the controls, for both the repacked and undisturbed soils. Surface placement of the liquid swine manure produced a slightly smaller K_{sat} in all repacked soil columns (Fig. 1). The K_{sat} in the repacked manured soils columns tended to decrease as the clay content in the soils increased.

Even after manure addition, the K_{sat} of the undisturbed silt loam columns was greater than that for the other two soil types between which there were minimal differences.

However, the use of the liquid swine manure on the undisturbed columns led to an increase in the measured K_{sat} values contrary to the expectations from results with the repacked columns. This increase was most obvious for the two finer textured soils, the silt loam and the silty clay (Fig. 1).

The measured K_{sat} for the Fox sandy loam soil columns were relatively similar under the two manure treatments in both the undisturbed and repacked soil columns, nevertheless with more variability being noted for the undisturbed columns. This similarity could once again be explained by the lack of structural stability of the repacked sandy loam soil when wetted. In contrast, for the columns of the two finer textured soils in their undisturbed state there was an increase in K_{sat} for both manure types relative to that in repacked soil.

Predictive value of measured parameters

Standard soil textural properties, measured soil porosity, soil organic matter content, and the van Genuchten's coefficients α and n (VG_{α} and VG_n) were evaluated for their significance in predicting K_{sat} . The two van Genuchten coefficients are indicators of the contribution that size, distribution, and continuity of soil pores make to water retention. Various researchers have associated the α coefficient with the bubbling pressure, while VG_n is a function of the pore size distribution (e.g., Blum et al. 2001).

Partial least square (PLS) regression analyses were performed separately for the repacked and undisturbed columns. Results for the repacked columns (summarized in Fig. 3a) showed that the only factor that yielded a clear predictive capability was the dry matter of the surface applied manure. This was inversely correlated to K_{sat} . For all other soil parameters, measured (percentages of clay, silt, sand, organic matter, soil porosity, and bulk density) or estimated (VG_{α} and VG_n) the PLS analysis indicated that they provided no clear predictive capacity (Fig. 3a). The first two PLS components had a regression coefficient of 0.50, mainly associated with the parameter "dry matter content of the manure". However, the combination of all parameters explained 93% of the variability in the K_{sat} data.

A straight correlation analysis confirmed the results obtained by the PLS analysis indicating that all considered predictors of K_{sat} were of significance at various levels (Table 3).

The same type of PLS analysis carried on the K_{sat} values for the undisturbed soil columns showed that the dry matter

Fig. 3. (a) Partial least squares (PLS) regression loading plot for the K_{sat} in the repacked soil columns and (b) PLS regression loading plot for the K_{sat} in the undisturbed soil columns. In the PLS loading plots each component (on the x and y axes) is followed in parenthesis by the x variance and the regression coefficient associated with the respective PLS component. The length of the line associated with each factor indicates the relative significance of the respective predictor in explaining the total variance in the measured data and the associated regression coefficient. The angle between the same lines indicates the level of collinearity between the respective predictors.

content of the manure was still useful as a predictive parameter, although its value was somewhat diminished (Fig. 3b). In addition, soil clay content was also useful, though in this case the parameter was inversely related to the measured value of K_{sat} . However, the clay-content parameter did not explain a great deal of the variation in K_{sat} , and was associated mostly with the second PLS component that had a compounded predictive capability as expressed by the associated r^2 of only 0.06 (Fig. 3b). The coefficient, VG_{α} , was the best predictor of the measured K_{sat} in the undisturbed columns and gave a predictive ability, as expressed by the associated r^2 , of 0.59. Together, all the parameters considered were able to account for 83% of the total variance associated with the K_{sat} data (see the sum of the x variance of the two PLS components as presented in

Table 3. Correlation of the considered parameters with the measured K_{sat} for repacked and undisturbed soil columns.

Soil disturbance status	$VG_{\alpha}^{\S}$	$VG_n^{\P}$	Manure dry matter content	Porosity (%)	% Sand	% Clay
Repacked	0.36 [†]	-0.43 [†]	-0.43 [‡]	-0.51 [‡]	0.49 [‡]	-0.56 [‡]
Undisturbed	0.61 [‡]	ns	-0.37 [†]	0.63 [‡]	ns	ns

Note: $N = 72$ for each correlation pair; ns, not significant.

*Significant at $p = 0.05$.

[†]Significant at $p = 0.01$.

[‡]Significant at $p = 0.001$.

[§]Average value of VG_{α} measured on equivalent non-manured columns were used.

[¶]Average value of VG_n measured on equivalent non-manured columns were used.

Fig. 3b), close to the value obtained for the repacked columns (see the sum of the x variance of the two PLS components as presented in Fig. 3a). The correlation analysis carried out for the undisturbed soil columns confirmed the relevance of the VG_{α} coefficient while indicating the lack of predictive capability associated with the soil textural indicators (Table 3). As expected, soil porosity in the undisturbed soil columns was directly correlated with VG_{α} and K_{sat} (Table 3). The unexpected inverse relationship between porosity and K_{sat} in the repacked columns (Table 3 and Fig. 3a) was almost certainly related to the collapse of the sandy loam soil after wetting and the swelling behaviour of the repacked silty clay soil.

A further simple correlation analysis was carried out for each manure treatment used (Table 4). This allowed the evaluation of the role of manure-induced variability on other considered predictors. In the case of the repacked soil columns liquid swine manure increased the predictive capability for every soil related parameter considered, while the solid beef cattle manure cancelled the significance of every predictor except the clay content of the soil. Again the only relevant predictors of K_{sat} in the undisturbed soil columns were the porosity and the VG_{α} coefficient. Nevertheless, the correlation between these two parameters and K_{sat} decreased with the addition of liquid manure, and even more so with the addition of solid beef cattle manure.

Field measurements

For soils close to saturation, rapid drainage within the first 6 h showed little difference between the two soils, although it was slightly greater on the finer textured soil than on the sandy loam (Fig. 4). The final infiltration volumes measured 20 h after irrigation were greater for the sandy loam soil than for the silt loam, following the application of either liquid or solid manure. Runoff was not observed on the sandy loam soil, but was observed on four occasions on the silt loam soil at initial volumetric water contents (i.e., soil water content before manure application and irrigation) of 24% and 34%, respectively (i.e., soil matric potential of 58 kPa and 8 kPa, estimated after Saxton et al. 1986); twice following the application of liquid swine manure (30% and 13% of applied irrigation) and twice following the application of solid manure from beef cattle (11% and 6% of applied irrigation).

Discussion

Soil porosity

Soil structure is critical for establishing hydraulic behaviour in macropores, whereas texture has a major impact on the hydraulic properties controlled by micropores (Lin et al. 1999). It is known that as the water input rises above the infiltrating capacity of a soil the excess will either be redirected away from the surface or will result in surface ponding. Infiltration rates, and therefore the water partitioning, are generally dependent on soil structural characteristics (Geeves et al. 1998). Therefore, while total soil porosity influences effective hydraulic conductivity and consequently both infiltration and water partitioning, the pore size distribution and the continuity of pores are more important factors. In this study the silty clay loam had the largest total porosity (Fig. 2). The sandy loam had the smallest total porosity but the largest volume of macropores of all three soils as indicated by the slope of the last part of the cumulative porosity function in Fig. 2. If the macropores determine the effective hydraulic conductivity this would suggest a larger K_{sat} value for the sandy loam. However this was not true; both the sandy loam and the silty clay had similar K_{sat} values. Consequently, this suggests that other pore characteristics such as pore continuity (Jacobsen et al. 1997) are particularly critical at this scale of experimentation.

van Genuchten's coefficients α and n (VG_{α} and VG_n)

The van Genuchten equation (eq. [1]) defines two fitting coefficients; VG_n is related to pore size distribution and VG_{α} is related to pore continuity. VG_n was inversely correlated with K_{sat} in the repacked cores, but there was no correlation for the undisturbed soil columns (Table 3). When liquid manure was added to the repacked cores the relevance of VG_n increased significantly (Table 4). This may be mostly attributed to the range of K_{sat} in the selected soils, the order of which is the following: sandy loam = silt loam > silty clay in the untreated repacked columns, but sandy loam > silt loam > silty clay in the repacked columns treated with liquid swine manure. Nevertheless addition of solid beef cattle manure changed the order of K_{sat} to silt loam > sandy loam > silty clay and thus the VG_n sequence, as determined for untreated soil columns, became irrelevant. However for the undisturbed soil columns VG_n , de-

Table 4. Correlation of the considered parameters with the measured K_{sat} for each manure treatment.

Manure type	Soil disturbance status	Porosity	% clay	% sand	% silt	VG_{α}	VG_n
No manure	Repacked	-0.58 [†]	-0.66 [†]	0.56 [†]	ns	ns	-0.47*
	Undisturbed	0.81 [‡]	Ns	ns	0.45*	0.819 [‡]	ns
Liquid swine manure	Repacked	-0.89 [‡]	-0.88 [‡]	0.89 [‡]	-0.74 [‡]	0.80 [‡]	-0.85 [‡]
	Undisturbed	0.70 [†]	Ns	ns	ns	0.66 [†]	ns
Solid beef cattle manure	Repacked	ns	-0.56*	ns	ns	ns	ns
	Undisturbed	0.57 [†]	Ns	ns	ns	0.49*	ns

Note: $N = 24$ for each correlation pair; ns, not significant.

*Significant at $p = 0.05$.

†Significant at $p = 0.01$.

‡Significant at $p = 0.001$.

Fig. 4. Infiltration of added water (irrigation and manure) beyond the top 30 cm of soil following surface application of liquid swine manure (LSM) or solid beef cattle manure (SCM) at 6, 12, and 20 h after the cessation of irrigation. The field drainage events have been grouped according to the soil matrix potential at the start of the experiment before manure addition and irrigation. The soil matrix potential has been calculated using the soil textural parameters and the measured volumetric water content as described by Saxton et. al (1986).

terminated in untreated undisturbed soil columns, was not correlated with K_{sat} for any of the manured or the control treatments (Table 4). While in the repacked columns the greatest value for VG_n was obtained in the silty clay columns, in undisturbed columns the greatest VG_n was obtained for the sandy loam columns (Table 2). If it is assumed that the VG_n pore size index increases with increased variability in the pore sizes (Blum et al. 2001) these results suggests that for the sandy soil the pore size distribution decreased with repacking, while it increased with repacking for the silt loam and the silty clay soils (Fig. 3a). Such behaviour led to the VG_n having no predictive value for the measured values of K_{sat} in the undisturbed soils (Tables 3 and 4). Thus the behaviour of VG_n was not consistent with the K_{sat} measurements that gave consistently smaller flow rates in the sandy loam columns, occasionally greater flow for the silty clay columns, and highest flow rates for the silt loam columns,

under both manure treatments. The pressure plate measurement of the water retention curves from which the VG_n was deduced does not estimate the free draining pores. Hence VG_n values are estimated for the matrix pores, while the K_{sat} in the undisturbed silt loam and silty clay soil columns are mostly dependent on the larger pores. In contrast, for the sandy loam soil, lack of structural stability led to the absence of such macropores and the VG_n mirrored more closely the state of disturbance of the soil columns and thus the K_{sat} (Table 2).

The lack of difference between the values of VG_{α} for the repacked and the undisturbed silty clay columns indicated the similarity between the hydraulic properties of the matrix of the undisturbed columns and the repacked columns. Repacking the silt loam decreased the air entry value, while for the sandy loam the air entry value increased with the sieving and repacking.

Manure impact

Addition of liquid manure resulted in similar or slightly decreased K_{sat} values for the repacked columns of all three soils. This decrease was more noticeable for the finer textured soils. This suggested that the pores became clogged, either due to the presence of the dry matter in the manure or to seal formation due to clay dispersion (Haynes and Naidu 1998). It is known that presence of interspersed hydrated ions favours clay dispersion (Shainberg and Singer 1988). The liquid phase of manure has a large concentration of salts (Sweeten 1998) and manure application results in an increase in the Na^+ concentration in soils (Chang et al. 1991). Addition of NH_4^+ ions, found mostly in the liquid manure can enhance clay dispersion (Haynes and Naidu 1998). However, it is questionable if the hydrated ions present in the manure are able to penetrate amongst the clay platelets rapidly after manure application, unless the clay platelets are initially dispersed by another mechanism, such as kinetic energy of water. Nevertheless the clay dispersion hypothesis seems to be supported by the inverse relationship between the clay content and the K_{sat} in the repacked cores treated with liquid manure (Table 3) and thus the greater decrease in K_{sat} that occurred in the two finer textured soils (Fig. 1). However, for the same liquid swine manure treatment, the textural properties of the undisturbed soils were not correlated with the measured K_{sat} (Table 3). On the contrary, K_{sat} increased in the two finer textured soils. If pore clogging or sealing due to the liquid manure occurred similarly to that in the repacked cores this could only be true for the smaller pores within the matrix while the larger pores would have remained unobstructed. Furthermore, the increase in K_{sat} suggests that stability of the larger pores may have been enhanced by the increased ionic strength of the pore solution, which could have caused shrinkage of the diffuse electrical double layer at the surface of charged particles, such as clays (Stotzky 1985). Under field conditions, if the matrix flow is restricted by seal formation or clogging of smaller pores the amount of incoming rain or irrigation water can overwhelm the transport capacity of the available macropores leading to ponding or surface runoff. These conclusions were supported by the field results where application of liquid swine manure led to both greater infiltration (Fig. 4) and runoff, even if the soil matrix was not saturated.

Solid manure from beef cattle had a relatively slow hydraulic conductivity ($K_{\text{sat}} = 1.6 \text{ cm h}^{-1}$). When the manure was added to either repacked or undisturbed soil the K_{sat} of the column was always reduced (Fig. 1). For the repacked soil columns the soil textural parameters and water retention parameters as measured for control columns were not correlated with the results of the K_{sat} measurements. This result differed from those obtained for the liquid swine manure suggesting that the difference was due to the increased dry matter added to the soils with the solid beef cattle manure. An exception was the clay content that still retained some predictive capability (Table 3). For the undisturbed soil columns the only factors that remained correlated with K_{sat} were VG_α and the total porosity; similar to the results obtained with the liquid swine manure (Table 3). How-

ever, as the measured K_{sat} values were also smaller than those measured for undisturbed soil and for soil treated with liquid swine manure, the greater dry matter addition also reduced the flow through the larger pores that effectively transported water in the cores with little or no organic matter addition. The manure apparently interferes with flow through the largest pores. Application of solid beef cattle manure to the field plots also resulted in reduced runoff as well as in reduced deep drainage. These results indicated that the application of solid beef cattle manure led to a greater water holding capacity of the soil-manure system. However as the manure itself contained over 75% water, any supplementary water retention capacity due to the contribution of incorporated bedding material was most likely very small (Barry 1999). Hence the water must have been retained within the soil profile, which is more likely if the smaller pores are primarily responsible for transporting water and storing it temporarily in the soil matrix. Thus the solid beef cattle manure favoured increased retention in the surface soil horizons.

Field infiltration patterns confirmed the capacity of the finer textured silt loam soil to allow faster initial transport through the larger pores that permit such rapid flow. Final infiltration volumes, 20 h from irrigation, were nevertheless greater for the sandy loam than the silt loam soil suggesting the significance of matrix flow for the coarser textured soil (Fig. 4). Addition of liquid manure to the finer textured silt loam did increase the run-off and limited the infiltration thus confirming the role of the surface sealing of pores observed in the core tests.

Conclusions

The hydraulic transport rates (K_{sat}) estimated from repacked soils did not predict the values for the same soils in their undisturbed field state, except in the case of an unstructured sandy soil indicating the superseding role of soil pore structure over the total soil porosity. Surface application of liquid swine manure reduced the matrix flow by blocking smaller surface pores and thus favoured accelerated flow through macropores in the two soils with greater structural stability. Application of liquid swine manure also favoured surface runoff when the capacity of the macropores to carry all the water available for infiltration was exceeded, and this effect was more obvious for the finer textured soils. Thus, better structured, finer textured soils allowed for fast vertical transport at the start of a water input event. There is likely an important role for continuous macropores for infiltration, but which also increases the risk that particulates such as pathogenic bacteria from manure might also be transported. Surface addition of solid waste material that has greater dry matter content can immediately limit the fast macropore flow while accentuating matrix flow. This effect reduces the risk of fast macropore infiltration and also the risk of surface runoff, and therefore reduces the risk of microbial contamination to both ground- and surface waters.

References

- Barrington, S., and Jutras, P.J. 1983. Soil sealing by manure in various soil types. Winter Meeting of the American Society of Agricultural

- Engineers. ASAE, Microfiche Collection, Fiche No. 83-4571.
- Barry, D. 1999. Transformation and losses in solid manure systems. In MCLONE 4. An integrated systems approach to manure handling systems and nutrient management. Enhancement of a computerized decision support system for manure management on hog farms. In Technical report submitted to Ontario Pork. Manure Systems Research Group, University of Guelph, Ont. pp. 29–38.
- Betzalel, I., Morin, J., Benyamini, Y., Agassi, M., and Shainberg, I. 1995. Water drop energy and soil seal properties. *Soil Sci.* **159**: 13–22.
- Blake, G.R.Z. 1965. Particle density. Methods of soil analysis. In Methods of soil analysis. Part 1. Physical and mineralogical methods. Edited by C.A. Black. American Society of Agronomy – Soil Science Society of America, Madison, Wis. pp. 371–375.
- Blake, G.R., and Hartge, K.H. 1986. Bulk density. In Methods of soil analysis. Part 1. Physical and mineralogical methods. Edited by A. Klute. American Society of Agronomy – Soil Science Society of America, Madison, Wis. pp. 363–375.
- Blum, V.S., Israel, S., and Larson, S.P. 2001. Adapting MODFLOW to simulate water movement in the unsaturated zone. In MODFLOW 2001 and Other Modeling Odysseys – Proceedings, International Groundwater Modeling Center (IGWMC), Colorado School of Mines, and the U.S. Geological Survey, 11–14 September 2001. pp. 60–65.
- Chang, C., Sommerfeldt, T.G., and Entz, T. 1991. Soil chemistry after eleven annual applications of cattle feedlot manure. *J. Environ. Qual.* **20**: 475–480.
- Eneji, E.A., Yamamoto, S., Honna, T., and Ishiguro, A. 2001. Physico-chemical changes in livestock feces during composting. *Commun. Soil Sci. Plant Anal.* **32**: 477–489.
- Geeves, G.W., Cresswell, H.P., and Murphy, B.W. 1998. Two indices of soil structure based on prediction of soil water processes. *Soil Sci. Am. J.* **62**(1): 223–232.
- Gerzabek, M., Kirchmann, H., Pichlmayer, H.F. 1995. Response of soil aggregates stability to manure amendments in the Ultuna long-term soil organic matter experiment. *Z. Für Pflanzenernährung Und Bodenkunde*, **158**: 257–260.
- Haynes, R.J., and Naidu, R. 1998. Influence of lime, fertilizer and manure applications on soil organic matter content and soil physical conditions: a review. *Nutr. Cycling Agroecosyst.* **51**: 123–137.
- Hillel, D. 1998. Environmental soil physics. Academic Press, San Diego, Calif.
- Jacobsen, O.H., Moldrup, P., Larsen, C., Konnerup, L., and Petersen, L.W. 1997. Particle transport in macropores of undisturbed soil columns. *J. Hydrol.* **196**: 185–203.
- Keren, R. 1990. Water-drop kinetic energy effect on infiltration in sodium-calcium-magnesium soils. *Soil Sci. Soc. Am. J.* **54**: 953–987.
- Lin, H.S., McInnes, K.J., Wilding, L.P., and Hallmark, C.T. 1999. Effects of soil morphology on hydraulic properties: II. Hydraulic pedotransfer functions. *Soil Sci. Soc. Am. J.* **63**: 955–961.
- Mace, A., Rudolph, D.L., and Kachanoski, R.G. 1998. Suitability of parametric models to describe the hydraulic properties of an unsaturated coarse sand and gravel. *Ground Water*, **36**(3): 465–475.
- Mathsoft Engineering and Education, Inc. 1998. MathcadPro version 8.01™ [computer program].
- McCoy, E.L., Boast, C.W., Stehouver, R.C., and Klavdivko, E.J. 1994. Macropore hydraulics: taking a sledgehammer to classical theory. In Soil processes and water quality. Edited by R. Lal and B.A. Stewart. CRC Press, Boca Raton, Fla. pp. 303–348.
- Minitab, Inc. 2004. Minitab™ release 14 statistical software [computer program].
- Morin, J., Benyamini, Y., and Michaeli, A. 1981. The effect of raindrop impact on the dynamics of soil surface crusting and water movement in the profile. *J. Hydrol.* **52**: 321–335.
- O'Connor, D.R. 2002. Report of the Walkerton inquiry. Part 1: The events of May 2000 and related issues. The Walkerton Inquiry, Toronto. pp. 502.
- Patni, N.K., Toxopeus, H.R., and Jui, P.Y. 1985. Bacterial quality of runoff from manured and non-manured cropland. *Trans. ASAE*, **28**: 1871–1877.
- Reynolds, W.D. 1993. Saturated hydraulic conductivity: Laboratory measurement. In Soil sampling and methods of analysis. Edited by M.R. Carter, Can. Soc. Soil Sci. Lewis Publishers, New York. pp. 589–598.
- Saxton, K.E., Rawls, W.J., Romberger, J.S., and Papendick, R.I. 1986. Estimating generalized soil-water characteristics from texture. *Soil Sci. Soc. Am. J.* **50**: 1031–1036.
- Shainberg, I., and Singer, M.J. 1988. Drop impact energy-soil exchangeable sodium percentage interactions in seal formation. *Soil Sci. Soc. Am. J.* **52**: 1449–1452.
- Stotzky, G. 1985. Mechanisms of adhesion to clays, with reference to soil systems. In Bacterial adhesion: Mechanisms and physiological significance. Edited by D.C. Savage and M. Fletcher. Plenum Press, New York, N.Y. pp. 195–254.
- Sweeten, J.M. 1998. Cattle feedlot manure and wastewater management practices. In Animal waste utilization: effective use of manure as a soil resource. Edited by J.L. Hatfield and B.A. Stewart. Ann Arbor Press, Chelsea, Mich. pp. 125–155.
- Topp, G.C., Galganov, Y.T., Ball, B.C., and Carter, M.R. 1993. Soil water desorption curves. In Soil sampling and methods of analysis. Edited by M.R. Carter, Can. Soc. Soil Sci. Lewis Publishers, New York. pp. 569–579.
- Unc, A., and Goss, M.J. 2003. Movement of faecal bacteria from manure through the vadose zone. *Water, Air Soil Pollut.* **149**: 327–337.
- van Genuchten, M.Th. 1980. A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. *Soil Sci. Soc. Am. J.* **44**: 892–898.