Impact of Saturated Hydraulic Conductivity on the Prediction of Tile Flow

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ABSTRACT

Preferential flow through macropores and other structural voids in field soils most often occurs at or near saturation. Our earlier research revealed significant differences in the value of the saturated hydraulic conductivity (K_s) of a glacial till soil in central Iowa when obtained with five different measurement techniques. The five techniques included one laboratory constant-head permeameter method and four in situ methods: disc permeameter, Guelph permeameter, velocity permeameter, and double-tube permeameter. Differences in measured K_s values were attributed to differences in sample size, the existence or absence of open-ended macropores, and measurement principles. In this study, we used the different K_s estimates in a two-dimensional numerical model, CHAIN_2D, to predict water flow into a subsurface tile drain in the same field. Comparisons between predicted and observed tile flows were made during four crop growing seasons. Preferential flow observed in the tile drain during large storm events was predicted best by the model when using K_s values measured with the disc permeameter method, which least disturbed the boundary conditions of the flow field and better accounted for the macropore structures of the field soil. Quantitative and qualitative findings suggest that the disc permeameter was best suited for the field site.

THE SATURATED hydraulic conductivity (K_s) is a key parameter needed for analyzing or modeling water flow and chemical transport in the subsurface soil. Several laboratory and in situ techniques have been developed during the past several decades to measure this parameter. The different techniques often show significant differences in K_s that reflect inherent experimental or mathematical limitations (Lee et al., 1985; Kanwar et al., 1989; Logsdon et al., 1990; Mohanty et al., 1991, 1994; Paige and Hillel, 1993; Gupta et al., 1993). One logical question that arises is how the different K_s measurements may impact predictions of flow and transport when used in a computer model. This question seems especially important when water flow or solute transport at or near saturation is considered in a macroporous field soil. In other words, K_s probably plays an especially important role in the vadose zone (between the soil surface and shallow groundwater table) during periods following heavy rainfall or irrigation. The objective of our study was to determine the impact of K_s values measured with four different techniques on the ability of the two-dimensional variably-saturated flow and transport numerical model (CHAIN_2D) to predict tile drain outflow from a macroporous, no-till, tile-drained agricultural field. For this study, the K_s measurement techniques included: (i) an in situ Guelph permeameter, (ii) an in situ velocity permeameter, (iii) an in situ disc permeameter, and (iv) a constant-head permeameter in the laboratory using detached soil cores.

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MATERIALS AND METHODS

Field Site

A 115 by 36 m field was selected at the Agronomy and Agricultural Engineering Research Center near Ames, IA. The experimental plot was part of the Field no. 5 that lies on a Wisconsin-age glacial-till soil of the Des Moines lobe with a maximum slope of 2%. The soils are Nicollet (fine-loamy, mixed, mesic Aquic Hapludoll) and Clarion (fine-loamy, mixed, mesic Typic Hapludoll) loams in the Clarion-Nicollet-Webster association. The experimental plot had been under no-tillage practice and continuous corn production since 1984. Singh et al. (1991) reported that 2 to 12% of the planar surface area of the field site was occupied by biological and structural macropores (>1-mm diameter), and that the macropore area decreased with increasing soil depth. Everts and Kanwar (1989) and Singh and Kanwar (1991) also showed the significance of macropore flow at the field site. A 20-m-thick layer of aquitard material with relatively low saturated hydraulic conductivity (0.001 m d^{-1}) at a depth of 3.9 m separated the lower confined aquifer from the upper unconfined aquifer at the field site. Heavy storm events at the site often cause the shallow groundwater table in this field to rise close to the soil surface. Parallel 1.22-m-deep subsurface drains at 36.6-m spacings drain excess water from different experimental plots at the field site. The 10.2-cm-diameter clay tile drains were installed in 1960. The drain system was assumed to be completely stabilized by the time of our investigation (1984–1990). Tile flow rates were measured daily throughout the crop growing season (April–October) using an automated flow measurement system at the downgradient end of the tile.

A series of K_s measurements was made in this experimental field at five sites at four different depths (15, 30, 60, and 90 cm) using five K_s measuring techniques. As no definite rule exists for knowing the actual measurement (soil) volume for the in situ techniques, we determined the depth intervals on the basis of visual examination of the profile stratigraphy and the suitability of different methods at different depths. Although some K_s measurements could be made near the soil surface (0–15 cm depth) using detached soil cores and disc permeameter technique, no measurement was possible using the Guelph permeameter. Thus, for this comparison study, we did not use the near-surface K_s measurements. The measurements were made in June and July 1990 during the corn growing season. Detailed descriptions of the K_s measurements and a comparison of the different techniques can be found elsewhere (Mohanty et al., 1994). Here we only briefly summarize the salient features of these techniques. The double-tube permeameter measurements in Mohanty et al. (1994) were not used in this study since experimental difficulties led to very few data points.

Guelph Permeameter Method

A Guelph permeameter (Reynolds and Elrick, 1986) is a constant-head permeameter that measures a composite of the vertical and horizontal K_s in the field. A 5-cm-diameter and 15-cm-deep vertical borehole was augured. Proper preparation

Abbreviations: K_s, saturated hydraulic conductivity; RMSE, root mean square error.

of the borehole is critical to accurate measurement of K_s; commercially available augers and a brush (designed for the Guelph permeameter) were used to make a clean borehole and to minimize wall smearing. Two sets of steady-state measurements were made at two different constant heads, and K_s was calculated using the calibrated relationship. Stable readings took from 1 to 3 h depending on the antecedent soil moisture condition. Obtaining stable readings was somewhat of a problem at sites having low conductivity owing to slowly declining readings, even after 4 to 6 h of infiltration, as pores became plugged by sediments. Other possible reasons for this behavior may include vertical–horizontal anisotropy in K_s and a water front moving through different soil layers.

Velocity Permeameter Method

A velocity (or falling-head) permeameter was adapted for field use (Merva, 1987). An 8.4-cm-diameter cylinder was pushed ≈7 cm into the soil. We experienced some soil compaction and macropore blockage when the sample cup was hammered into the ground. The top of the cylinder was closed and connected to two hoses, one of which was connected to a reservoir providing water for infiltration. The second hose was used to vent air from the cylinder and connect it to an observation tube. Saturated hydraulic conductivity for the soil inside the cylinder was calculated from cylinder geometry (i.e., soil length and core diameter) and the rate at which the water level in the observation tube decreased. For every soil core, several estimates were made as the wetting front moved through the soil. When the wetting front moved below the in situ soil core, K_s estimates approached a pseudoconstant value that was taken as the hydraulic conductivity of the sample. Depending on depth and permeability, one complete saturated-conductivity reading took from 15 to 45 min.

Disc Permeameter Method

A disc permeameter is a constant-head infiltrometer that can operate at either a positive or a negative head (Perroux and White, 1988). A precursor of this method is the suction crust infiltrometer (Hillel and Gardner, 1969, 1970; Bouma, 1982; Booltink et al., 1991). Suction crust infiltrometers, however, have never been popular since making a crust is rather cumbersome. On the contrary, disc permeameters are being widely used because of their ease of operation. Infiltration takes place through a 2-cm layer of between 0.25- and 0.42-mm-diameter (40–60 mesh) sand inside a 25.4-cm-diameter ring. Sand placed on the surface was estimated by the Kozeny–Carman equation to have a minimum hydraulic conductivity of 4881.6 cm d^{-1} (Carman, 1937). The K_s were estimated based on infiltration measurements made by maintaining 0 to 10 mm of positive head in the permeameter. Procedural details on the hydraulic conductivity estimation and the supporting evidence of using a small positive head were described earlier in a parallel study (Everts and Kanwar, 1993). A single infiltration reading required ≈50 min on average. Because the instrument sits on top of the soil without causing much soil disturbance, readings could be obtained for all four depths unless hampered by a high water table. When the supply conditions changed from tension to ponding, the sorptivity value doubled or tripled in our study. Similar trends were noted by Perroux and White (1988) in their original study, indicating the relatively larger contribution of macropores under ponded conditions. One limitation of the disc permeameter is that for very permeable soils the value of K_s during a short time interval is often limited by the conductance of the contact material (sand) and the porous membrane of the permeameter (Reynolds and Zebchuk, 1996a).

Constant-Head Permeameter Method

Measurements of K_s in the laboratory (Klute, 1965) were based on direct application of Darcy's law to a saturated soil column of uniform cross-sectional area. A hydraulic-head difference was imposed on the soil column, and the resulting flux of water was measured. Five replicated detached soil cores, 7.6 cm long and 7.6 cm in diameter, were collected from the different depths using a Uhland core sampler. All cores were carefully inspected for cracks resulting from core recovery; only intact cores were used further. The cores were saturated in the laboratory by wetting from the bottom, and K_s was measured under a constant head. This method measured the vertical conductivity. Limitations experienced with this method included some soil compaction during core extraction, wall leakage in loose samples, and piping due to the presence of worm holes or root channels open at both ends of the soil core. Because high moisture contents caused compaction of most soil samples at the deeper depths, no good samples were left for analysis below the depth of 90 cm. The average time required to obtain steady-state readings for the soil cores was ≈45 min.

Numerical Methods

The CHAIN_2D computer model (Simunek and van Genuchten, 1994), modified to apply piecewise continuous hydraulic functions (Mohanty et al., 1997), was used to simulate two-dimensional isothermal saturated–unsaturated flow through the rigid soil in a cross section perpendicular to the tile drain (Fig. 1). The use of piecewise-continuous hydraulic functions is a simple and yet practical approach for handling preferential flow in field soils (Mohanty et al., 1997); however, note that the definition of field-scale preferential flow (Mohanty et al., 1997) differs operationally from bypass flow or macropore flow (Booltink and Bouma, 1991). Recently, the modified CHAIN_2D model was field tested in a semiarid condition and found to be performing reasonably well to simulate water and nitrate transport to a tile drain following the flood irrigation events in Las Nutrias, NM (Mohanty et al., 1997, 1998).

Considering two-dimensional isothermal Darcian flow, the governing flow equation in CHAIN_2D is given by the Richards' equation

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x_i}\left\{K\left[K_{ij}^A\left(\frac{\partial h}{\partial x_j}\right) + K_{iz}^A\right]\right\} - S \qquad [1]$$

where θ is volumetric water content ($L^3\ L^{-3}$), h is the soil water pressure head (L) (for notational convenience assumed to be positive downward), S is a sink term (T^{-1}), x_i (i = 1,2) are the spatial coordinates (L), t is time (T), K_{ij}^A and K_{iz}^A are components of a dimensionless anisotropy tensor $\mathbf{K}^A$, and K is the unsaturated hydraulic conductivity function ($L\ T^{-1}$). As suggested by Mohanty et al. (1997), piecewise-continuous hydraulic functions $\theta(h)$ and $K(h)$ were used to keep the unsaturated hydraulic parameters the same and independent of the different saturated hydraulic conductivity values. For a multimodal pore-size distribution, the soil water retention and hydraulic conductivity functions can be written as (Mohanty et al., 1997, 1998):

$$\theta(h) = \textstyle\sum_i w_i\theta_i(h) = \sum_i w_i\left\{\theta_{r,i} + \dfrac{\theta_{s,i} - \theta_{r,i}}{[1 + (\alpha_i|h|)^{\beta_i}]^{\gamma_i}}\right\}$$

$$h \le h_\theta^* \qquad [2]$$

$$\theta = \theta_{s(i=1)} \qquad h > h_\theta^* \qquad [3]$$

$$K(h) = \textstyle\sum_i k_iK_i(h) =$$

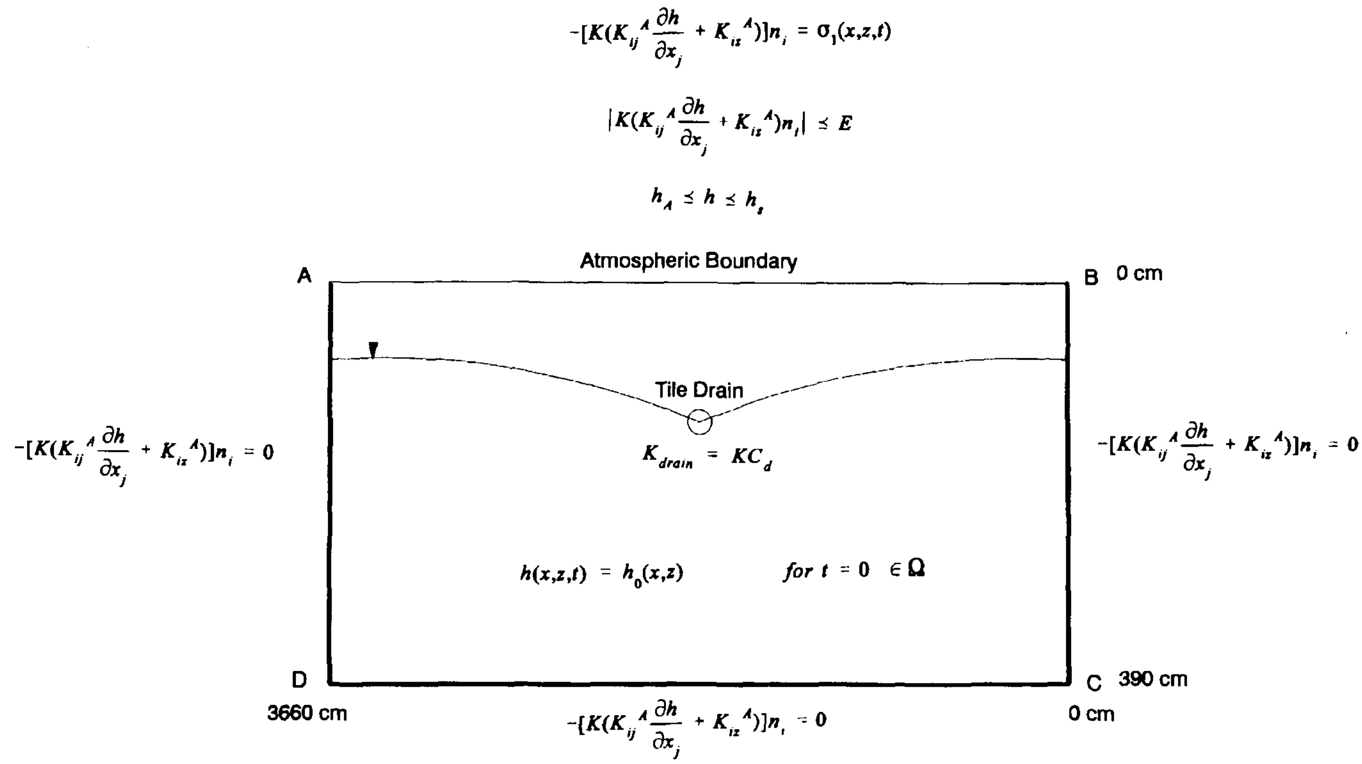

Fig. 1. Finite element flow domain where σ (-) are prescribed (rainfall water flux) functions of x, z, and t; and n_i are the components of the outward unit vector normal to the boundary Γ_{AB}; E is the maximum potential rate of infiltration or evaporation under the current atmospheric conditions; h is the pressure head at the soil surface, and h_A and h_s are, respectively, minimum and maximum pressure heads allowed under the prevailing soil conditions. K_{drain} is the adjusted hydraulic conductivity ($L\ T^{-1}$), and C_d is a correction factor (-).

$$\sum_i k_i \frac{\{1 - (\alpha_i|h|)^{\beta_i - 1}[1 + (\alpha_i|h|)^{\beta_i}]^{-\gamma_i}\}^2}{[1 + (\alpha_i|h|)^{\beta_i}]^{\gamma_i/2}}$$

$$(\gamma_i = 1 - 1/\beta_i) \qquad h \le h_K^* \qquad [4]$$

$$K_{ni}(h) = K^* + K^*[\exp(h - h^*)\delta - 1]$$
$$h_K^* < h \le 0 \qquad [5]$$

$$K_{ni}(h) = K^* + K^*[\exp(-h^*)\delta - 1] \qquad h > 0 \qquad [6]$$

where,

K_i	is the hydraulic conductivity for capillary-dominated flow domain i ($L\ T^{-1}$),
K_{ni}	is the hydraulic conductivity for noncapillary-dominated flow domain ni ($L\ T^{-1}$),
$\theta_{s,i}$	is the saturated water content for capillary-dominated flow domain i ($L^3\ L^{-3}$),
$\theta_{r,i}$	is the residual water content for capillary-dominated flow domain i ($L^3\ L^{-3}$),
h	is the equilibrium soil water pressure head of the "bulk" soil (across all flow domains) (L),
$h_K^* \approx h_\theta^* = h^*$	is the critical or break-point soil water pressure head where flow changes from capillary-dominated to noncapillary-dominated flow, or vice versa (L),
K^*	is the hydraulic conductivity corresponding to h^* (LT^{-1}),
δ	is a fitting parameter representing effective macroporosity or other structural features contributing to noncapillary dominated flow (L^{-1}),
α_i, β_i	are the hydraulic shape parameters (van Genuchten, 1980) for the capillary-dominated flow domain i (L^{-1}, -),
i	is the number of capillary-dominated flow domains. For $i = 1$, the sum type multimodal van Genuchten-Mualem hydraulic functions (i.e., Eq. [2] and [4], reduce to the original unimodal van Genuchten–Mualem functions),
ni	is the noncapillary-dominated flow domain,
w_i	is the weighting factor for capillary-dominated flow domain i (-); subjected to $\Sigma w_i = 1$, and $0 < w_i < 1$, and
k_i	is the saturated hydraulic conductivity for capillary-dominated flow domain i ($L\ T^{-1}$); subjected to $\Sigma k_i = K^*$.

Besides K_s, unsaturated hydraulic properties [$K(h)$ and $\theta(h)$ functions] were measured between −5 and −15 000 cm of soil water pressure head using the detached soil cores and adopting the multistep outflow procedure (Gardner, 1956; Richards, 1965). These hydraulic functions are essential for the numerical flow modeling. Using a nonlinear curve fitting procedure, we found that the soil hydraulic properties were best described using a bimodal pore-size distribution with one capillary and one noncapillary flow domain matched at $h^* = -5$ cm. In a few instances, at 30- and 60-cm depths, K_s values measured with the Guelph permeameter were lower than the unsaturated K at −5 cm pressure head measured using the soil cores. For these cases, we used unimodal hydraulic functions with the unsaturated hydraulic conductivity connected to K_s measured with the Guelph permeameter. Table 1 presents the hydraulic parameters of the soil at different depths in the experimental plot.

For the numerical simulations, we discretized the flow domain (cross section) into 9185 nodes and 8964 quadrilateral elements. Based on the hydraulic conductivity measurements,

Table 1. Parameters of bimodal piecewise-continuous hydraulic functions for different soil horizons.

Depth	$\theta_{s,i=1}$	$\theta_{r,i=1}$	α	β	K^*	h^*	δ Guelph	δ Velocity	δ Disc	δ Soil core
cm	$cm^3\ cm^{-3}$		cm^{-1}	–	$cm\ d^{-1}$	cm	cm^{-1}			
0–15	0.467	0.011	0.018	1.63	0.555	−5	0.52	0.62	0.84	0.03
15–30	0.462	0.020	0.015	1.60	2.40	−5	–	0.21	0.72	0.65
30–60	0.435	0.090	0.020	1.50	4.55	−5	–	0.36	0.54	0.22
60–390†	0.430	0.080	0.023	1.47	11.20	−5	0.17	0.31	0.40	–

† As soil cores at the 90-cm depth in our study plot were compacted, unsaturated hydraulic conductivity measurements from an adjacent plot were used for our modeling study.

the soil profile was divided into four soil horizons: 0 to 15, 15 to 30, 30 to 60, and 60 to 390 cm. These four horizons were further subdivided into a total of 167 layers for numerical simulation purposes. Relatively fine (0.1–1 cm) discretizations were used near the soil surface, across horizon interfaces, and around the subsurface tile drain to enable accurate description of abrupt changes in local fluxes and hence pressure gradients. For the simulations, we used a time-variant evapotranspiration rate assuming a normalized constant water uptake distribution across the top 60 cm of the soil profile in accordance with the approach of Feddes et al. (1978) and Simunek and van Genuchten (1994). Daily potential evapotranspiration rates were estimated using atmospheric data from a nearby weather station 2 km away. Daily precipitation data were also used from the same weather station. Water table elevations estimated from the groundwater monitoring wells along the plot boundary were used to define the initial conditions in the two-dimensional flow domain (Fig. 1), Ω. Time-dependent precipitation rates at atmospheric boundary nodes, and no-flow conditions along impermeable bottom boundary nodes, were invoked. We simplified the two hydrologic boundaries (Γ_{AD} and Γ_{BC}, Fig. 1) by assuming them to be impermeable, thus neglecting regional flow contributions. The tile drain at the center of the plot was treated as a boundary node surrounded by four regular square elements with adjusted hydraulic conductivities according to the electric analog approach of Vimoke et al. (1963) and Fipps et al. (1986). Flow initial and boundary conditions for our initial value problem are shown in Fig. 1.

RESULTS AND DISCUSSION

Measurement of Saturated Hydraulic Conductivity

Values of K_s obtained with the above methods at different depths of our experimental field site, comprising several plots and tile drains, were previously given in Tables 2 through 4 of Mohanty et al. (1994). In this study, we will focus our modeling effort on a single plot for which comprehensive tile flow data are available

Table 2. Saturated hydraulic conductivity (K_s) measured by different methods at Site 5 (Tile 4) (after Mohanty et al., 1994).

Depth	Method: Guelph†	Velocity†	Disc†	Soil core§
cm	$cm\ d^{-1}$			
15	7.40	12.18	36.89	0.62
30	0.09	6.76	88.99	60.13
60	1.63	26.44	66.78	14.01
90	26.78	53.05	83.72	cs¶

† No replications (i.e., one measurement for each depth at Site 5).
§ Geometric mean of five replicates.
¶ cs is compacted soil sample.

(representing Tile 4 and Site 5 of Mohanty et al., 1994). Values of K_s for this plot are presented in Table 2. Important inferences from the K_s comparisons (Mohanty et al., 1994) were that (i) the Guelph permeameter yielded the lowest average K_s values, possibly because of small sample size, vertical–horizontal anisotropy, wall smearing, and air entrapment; (ii) the laboratory method produced the greatest variability at shallow depths (15 and 30 cm), presumably because of smaller sample size, the presence or absence of open-ended macropores, and variable soil compaction during core extraction; (iii) the velocity permeameter led to K_s values that were close to values estimated from detached soil cores measured in the laboratory, probably because of forced vertical flow in both cases; and (iv) the disc permeameter predicted higher K_s values in comparison with other in situ methods, probably because the larger sample sizes contained more intact macropores. This is in agreement with Anderson and Bouma (1973), Lauren et al. (1988), and Bouma (1991), who claimed saturated hydraulic conductivity increases with the sample volume. Because of their comparable values (Mohanty et al., 1994), velocity permeameter data were used in lieu of unavailable laboratory soil core data at the 90-cm depth for modeling purposes. We note also that, by principle, different in situ methods measure different combinations (ratios) of vertical and horizontal K_s, and since no pure vertical or horizontal K_s measurements could be made in situ, K_s in this study is assumed to be isotropic.

Simulation Results

Figures 2 through 5 compare measured daily tile flow over four crop growing seasons (April–October) during 1984 to 1990 with flow predicted by CHAIN_2D using different K_s values (or δ in the bimodal hydraulic functions) obtained from the four K_s measurement methods. Simulations for 1985, 1988, and 1989 were excluded since no or very little flow in the tile drain was observed in these drier years. The comparisons of simulated and measured tile flow indicates that tile flow in this field is very sensitive to K_s (or δ in the bimodal hydraulic functions). In addition to K_s, precipitation intensity and evapotranspiration rate influenced the tile flow pattern across each crop growing season. In 1984 (Fig. 2), during the early stages of corn growth, a lower evapotranspiration rate and heavy precipitation resulted in high tile flow. During the late crop growth stage (mature corn), however, the moderate amount of precipitation was

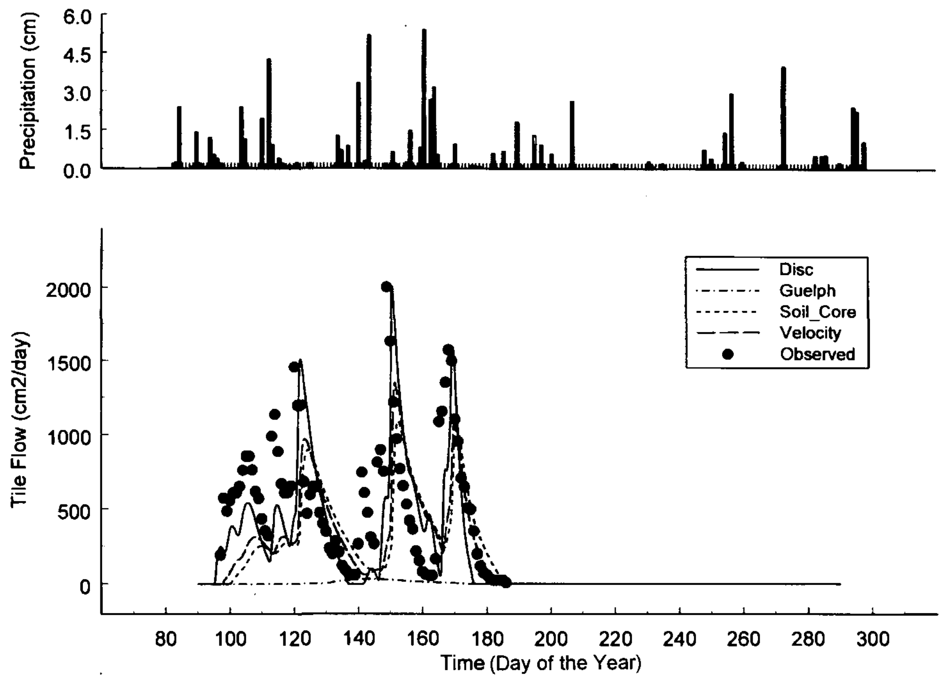

Fig. 2. Comparison of observed and predicted tile flow during the crop growing season of 1984 at the field site using different K_s. Also shown are precipitation dats at a nearby weather station during the same period.

mostly consumed by evapotranspiration and did not produce substantial amounts of measured or predicted tile flow. In 1986 (Fig. 3), several flow peaks could not be captured by any of the simulations, perhaps indicating inaccurate evapotranspiration estimates, unrepresented runoff, base flow, regional flow, or some other process not accounted for in the model. In early 1987 (Fig. 4), the model often underpredicted tile flow for different precipitation events, while the opposite was the case in the later part of 1990 (Fig. 5). These findings suggest that the model could be further improved by accommodating some of the above-mentioned field-scale flow processes. Other possible reasons for the discrepancies between observation and prediction include spatial-temporal variability of the soil hydraulic properties, precipitation and groundwater table variability across the relatively large field, and insufficient frequency (i.e., daily values) of tile flow measurements to capture the sharp peaks that often occurred following heavy precipitation. Also the frequency, intensity, and amount of precipitation

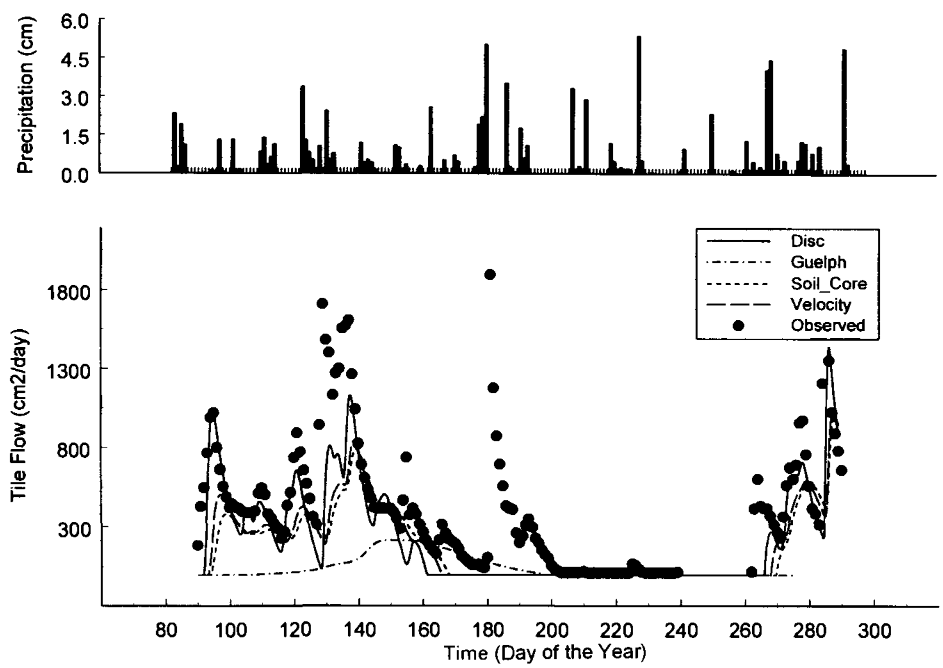

Fig. 3. Comparison of observed and predicted tile flow during the crop growing season of 1986 at the field site using different K_s. Also shown are precipitation data at a nearby weather station during the same period.

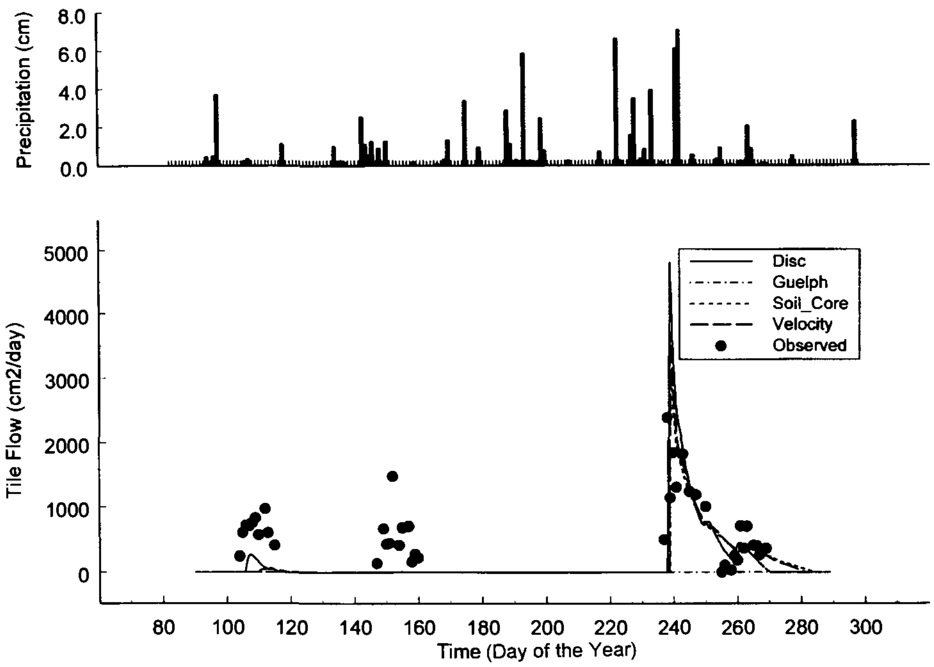

Fig. 4. Comparison of observed and predicted tile flow during the crop growing season of 1987 at the field site using different K_s. Also shown are precipitation data at a nearby weather station during the same period.

across the rolling landscape near the field site was highly variable. Hence, precipitation measured at the weather station may sometimes be inaccurate for our simulation of the experimental plot. Still, with the exception of the above-mentioned periods, the model seemed to perform well, certainly in a qualitative sense. Besides these qualitative comparisons, goodness-of-fit of the model predictions were objectively evaluated for different crop years and K_s measurement techniques using the root mean square error, RMSE (Table 3). This is defined as (Loague and Green, 1991)

$$\mathrm{RMSE} = \frac{100}{\overline{M}}\left[\frac{1}{N}\sum_{i=1}^{N}(M_i - S_i)^2\right]^{0.5} \qquad [7]$$

where M_i is the measured tile flow, S_i is the corresponding tile flow simulated by the model, N is the number of measurements, and $\overline{M}$ is the mean of the measured tile flow. A smaller RMSE (percentage) indicates a more accurate simulation.

Given the same unsaturated hydraulic and retention

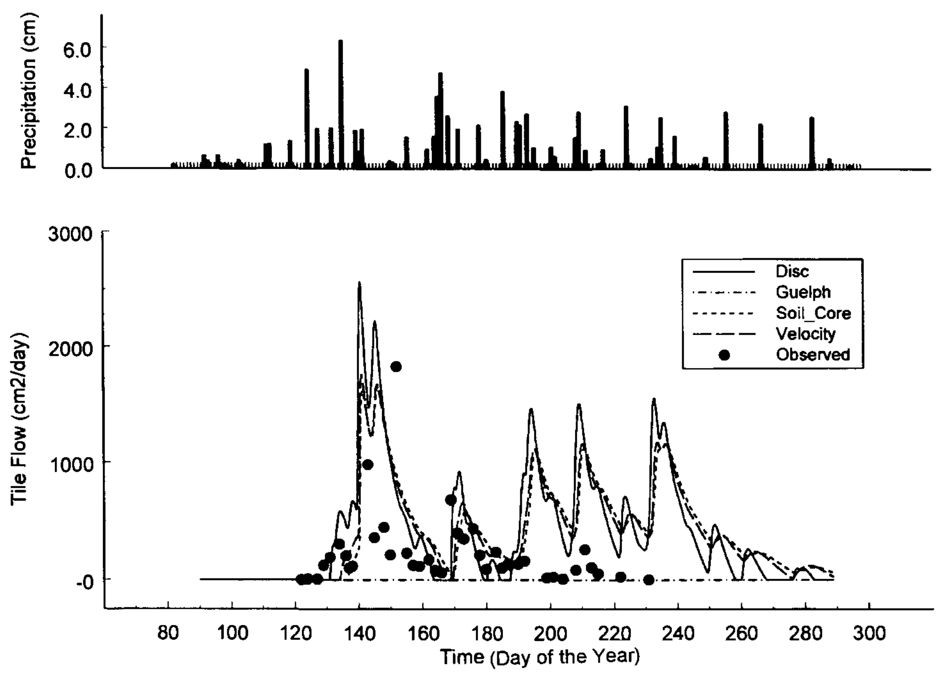

Fig. 5. Comparison of observed and predicted tile flow during the crop growing season of 1990 at the field site using different K_s. Also shown are precipitation data at a nearby weather station during the same period.

Table 3. Root mean square error (RMSE) for the tile flow predictions.†

Year	Method				Number of observations
	Guelph	Velocity	Disc	Soil core	
	%				
1984	122.1	87.7	71.5	94.2	91
1986	132.4	92.7	80.7	96.4	180
1987	127.4	110.5	128.0	100.8	43
1990	174.8	209.8	250.4	210.4	41

† Zero flow(s) or missing observation(s) because of any other reason were not used in the root mean square error (RMSE) computation.

functions, initial soil water conditions, and flow boundary conditions, tile flow predictions with the lowest K_s values (the Guelph permeameter) generated the lowest peaks and longest tails in comparison with predictions using higher K_s estimates of the other methods. The high K_s estimates of the disc permeameter produced flow with the highest peaks and shortest tails. Predictions using K_s obtained with the laboratory constand-head permeameter and the velocity permeameter produced intermediate tile flow rates during heavy storm events. Using quantitative evaluation procedure, disc permeameter K_s produced the lowest (best) RMSE for 1984 and 1986 (Table 3). In 1987 and 1990, however, all K_s methods produced relatively high (>100%) RMSE. Note that RMSE calculated using the Guelph permeameter estimated K_s in 1990 was lowest among all four methods. Careful examination of Fig. 5, however, indicated the zero (predicted) flow by using the Guelph permeameter K_s for the entire crop growing season. Thus, for a more unbiased evaluation of these techniques, a prudent combination of qualitative (e.g., graphical) and quantitative (e.g., RMSE) evaluation methods should be used. In general, K_s measured with a disc permeameter gave a better qualitative representation of the soil's matrix and macropore contributions to the hydraulic conductivity than the other three methods.

As pointed out by several early users and found in this study, limitations of the Guelph permeameter include smearing of the well wall during preparation, clogging of the soil pore structure by sedimentation, and artifacts involved in the original two-head analysis. These problems all lead to lower K_s estimates (e.g., Kanwar et al., 1989; Mohanty et al., 1991, 1994; Gupta et al., 1993; Paige and Hillel, 1993). In recent years, several researchers have tried to alleviate some of these problems to make the Guelph permeameter more representative and robust for in situ K_s measurements. Possible modifications and improvements include chipping of the well wall to open smeared pores under dry conditions, using wire screens and filter material to prevent sinking of the reservoir tip and limit sedimentation, and using an improved one-head mathematical analysis to avoid negative numbers (Elrick and Reynolds, 1992; Reynolds et al., 1992; Reynolds, 1993; Reynolds and Zebchuk, 1996b; W.D. Reynolds, 1997, personal communication). Reynolds and Zebchuk (1996b) reported improvement in K_s estimation by adopting some of these modifications in experimental procedure and data analysis. More recently, Bosch (1997) rebutted the earlier claims of improvement of K_s estimation using single-head analysis over two-head analysis (as used in this study) for any fine textured soil. Once these differences are resolved completely and an improved Guelph permeameter methodology is commercially available, similar comparative studies for different methods should be made to evaluate its performance under different soil and hydrologic conditions.

Our results also indicated that the K_s estimates obtained with the velocity permeameter and laboratory constand-head permeameter methods led to underpredicted tile flow rates. These two methods yield strictly vertical K_s measurements. In reality, hydraulic properties of the glacial till soil at the field site are probably not completely isotropic as assumed in our model. Also, these two methods use relatively small soil cross-sectional areas during measurements, and the bottom boundary conditions assumed by these methods may not be representative of flow processes in the field. By comparison, the disc permeameter method is based on three-dimensional flow pattern, and appeared to lead to a better model simulations of the tile flow behavior at our field site.

SUMMARY AND CONCLUSIONS

Differences in K_s resulting from the different measurement techniques should reflect differences in sampling volumes, the degree to which the pore-size distribution of the soil is altered by the techniques, differences in imposed flow boundary conditions, and differences in the one- or multidimensional flow pattern forced by the techniques. This study was designed to test the applicability of several K_s measurement techniques when used for numerical simulation of tile flow in a macroporous agricultural soil. Field-scale measurements and modeling of flow indicated the importance of K_s for predicting tile flow during high and low precipitation events with different evapotranspiration rates during the crop growing season. Observed and simulated tile flow matched better during the crop growing seasons when using disc permeameter K_s estimates than when using K_s measured with any of the other three methods. It is likely that this result reflects the fact that a disc permeameter better represents the natural flow conditions. Moreover, its ease of operation and minimal pore structure disturbance during the hydraulic conductivity measurements seem to give this technique additional advantages over other methods.

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