HYDRAULIC CONDUCTIVITY OF A LAYERED SOIL PROFILE MEASURED BY PONDED INFILTRATION TECHNIQUE

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Introduction

Hydraulic conductivity is the significant soil physical property for drainage design and research. The conductivity K_{sat} is needed for calculating drain spacing with steady-state equations. This parameter is also required for the description of water movement into the soil profile. Agrochemicals like nutrients and also pesticides can move with water through the soil profile to ground water. Thus knowledge of hydraulic conductivity is needed to assess the potential for ground water pollution.

Hydraulic conductivity can be measured both in the laboratory and in the field. The objective of this study was to select the method and the hydraulic conductivity measurement technique for the four main horizons of the Clermont silt loam soil, to provide data for studying drainage performance and water quality on a field experimental site.

Materials and Method

Hydraulic conductivity for layered soil is difficult to estimate. An example of such a type of soil is Clermont silt loam in the southern part of Indiana. The soil has a shallow water table during winter and early spring, but during the summer the water table is deep and provides an opportunity to measure infiltration for each layer separately. In order to estimate the hydraulic properties of this soil a ponded infiltration technique was chosen.

The infiltration experiment was performed on Clermont silt loam at the Southeast Purdue Agricultural Center (SEPAC) near North Vernon in Jennings County, Indiana, USA. Subsurface plastic drains were installed at 5, 10, 20 and 40 m spacing, at 75 cm nominal depth, and 0.4% nominal slope. There are two replications of each spacing grouped into blocks. Three drain lines (225 m long) were installed at each spacing. The 40 m spacing is considered to be the control (essentially undrained) treatment. Corn (Zea mays L.) was planted over the entire experimental area each year beginning in 1984 (Larney et al., 1988).

The Clermont profile was developed in loess over glacial till and is dominated by silt loam texture to a depth of 235 cm. Below the plow layer, the 24 to 38 cm and 38 to 64 cm horizons have very weak platy and weak subangular blocky structure, respectively. The 96 to 145 cm horizon has brittle material within the prisms, but the prisms are relatively small, 5 to 10 cm across. The 145 to 235 horizon has very coarse prisms, and conspicuous silt and clay films on the prism surfaces. It is a well developed fragipan according to current definitions [King and Franzmeier, 1981]. Below the fragipan, at a depth at 235 cm, is the paleosol surface. The change in soil properties there is quite apparent when boring with an auger because of the 10% clay increase, the increase in firmness and the morphology of the paleosol. In this Clermont profile the upper material, 0 to 235 cm, has more than 53% silt; below 235 cm the material has less than 43% silt. The sand content of the upper material, 9 - 26%, is higher than in typical loess. The clay content of the Clermont soil reaches an upper maximum of 26% in the 96 - 145 cm horizon and a second maximum of 36% in the paleosol. Sand content increases downward in the paleosol (King and Franzmeier, 1981)

The method used to measure infiltration was based on the cylinder infiltrometer method. Cylinder infiltrometers frequently have a diameter of about 30 cm and a height of 20 cm, and they penetrate the soil about 5 cm (Bouwer, 1986). Unfortunately, the cylinder infiltrometer diameter is too small for an accurate measurement. A part of the flow below cylinder infiltrometers is not vertical but diverges laterally. The infiltration rate inside the infiltrometer will then be higher than the true infiltration rate for vertical flow. Lateral divergence can be caused by capillary forces, by layers of reduced hydraulic conductivity deeper in the profile, and by the water depth in the infiltrometer.

Lateral divergence by capillary forces is due to the fact that pressure heads in the unsaturated soil adjacent to the infiltrometer are less (more negative) than those in the wetted zone directly below the infiltrometer, thus creating a hydraulic gradient radially away from the wetted zone. This can occur in uniform as well as in layered soils. The overestimation of the vertical infiltration rate due to lateral capillary forces depends on the ratio between the cylinder diameter d and the unsaturated-flow capability of the soil h_{cr}. Analyses with a resistance network showed that the measured final infiltration rate gives the true vertical infiltration rate (which theoretically is equal to hydraulic conductivity of wetted zone) correctly only if $h_{cr}/d = 0$. For the true vertical infiltration rate of the soil is necessary to use cylinders with such large diameters that the ratio h_{cr}/d is essentially zero (Bouwer, 1986).

Restricting layers deeper in the soil profile also can cause lateral flow below cylinder infiltrometers. If under those conditions only a small surface area is inundated, as in a cylinder infiltrometer, a perching groundwater mound can establish itself above the restricting layer. This mound can spread laterally and the infiltrated water can move through the restricting layer over a horizontal area larger than covered by the infiltrometer. The infiltration rate in the infiltrometer will then exceed the rate that will occur when the entire soil surface is inundated and all water has to move straight down through the soil and the restricting layer. The difference between the final infiltration rate from the infiltrometer and that for true, vertical infiltration rate depends on the hydraulic conductivity of the profile and on the depth of the restricting layer (Bouwer, 1986).

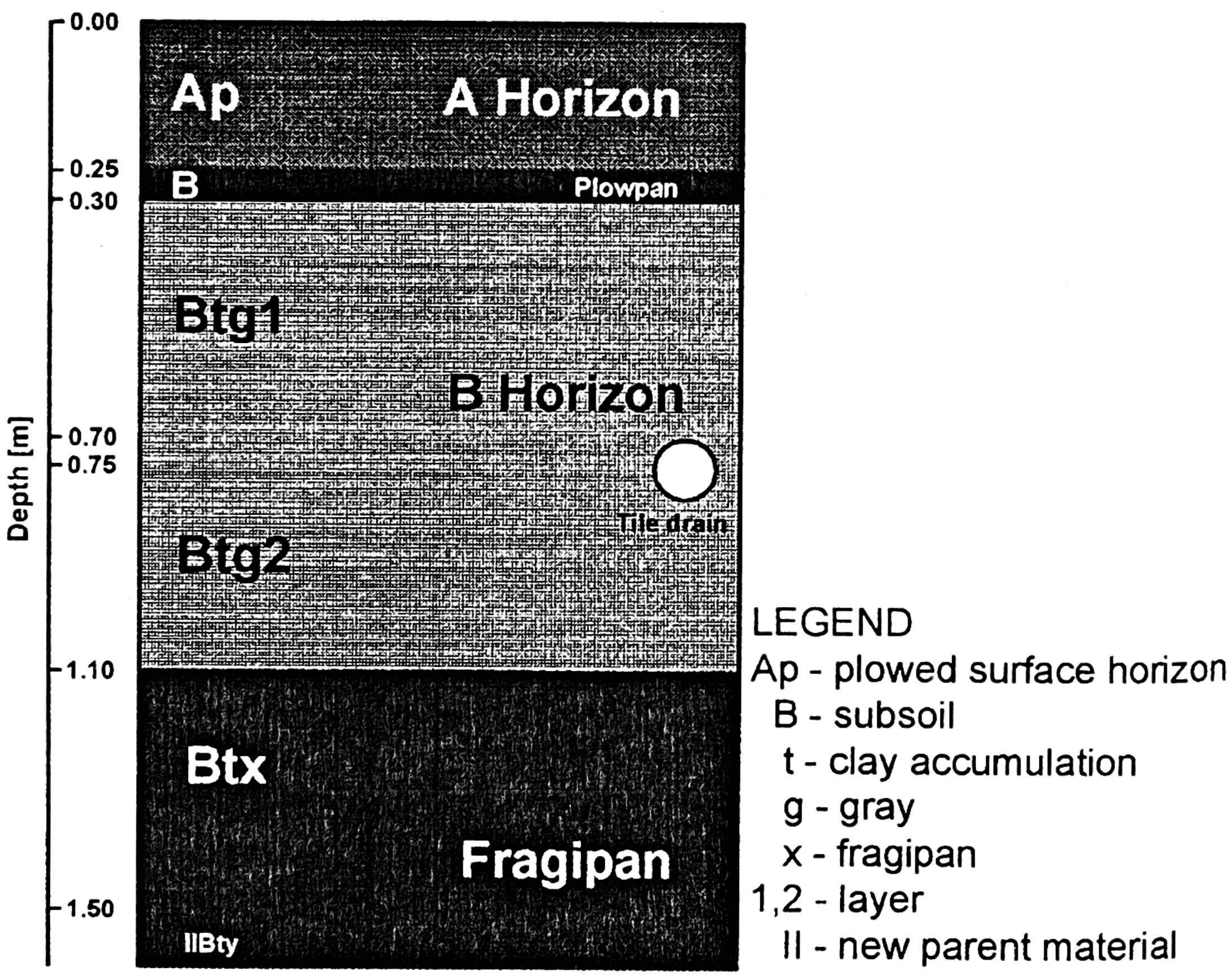

Fig. 1 The soil profile description

To avoid these problems, the current study used large square metal infiltrometers instead of small cylinders. Equipment used for this method included: 1.20m by

1.20m metal frame, 200 liter barrel, float valve, indicator tube and stop watch. The equipment maintained a constant head of water within the frame, and the volume of water infiltrated was determined by measuring volume of water remaining in the supply barrel. Saturated hydraulic conductivity was estimated when the readings reached a steady state, usually within two hours.

The experiment was done at six depths (5, 25, 30, 75, 110, 150 cm) in four different places in the field. The horizons were: surface, plow pan, top of the B horizon, middle of the B horizon, top of the fragipan, fragipan (fig.1). The metal frame was first inserted into the soil surface, and the soil surface was cleaned with a vacuum cleaner. After infiltration measurements at that depth, the soil was allowed to dry for several days to a week. The soil was then dug out to the next depth, being carcful to not compact the soil during the process. A fresh soil surface was prepared by gently digging the last few centimeters of the excavation and vacuuming loose soil. The process of infiltration measurement, drying, and excavating to the next depth was repeated in the same soil pit for each depth of interest and replicated in four soil pits.

Results and Discussion

Measured field data were statistically fitted to infiltration equation of Philip (Philip, 1987):

$$I = S \times t^{0.5} + A \times t \qquad (1)$$

where:

I - cumulative infiltration [mm]

t - time [h]

S - sorptivity [mm/h$^{0.5}$]

A - parameter [mm/h]

Philip equation was also used to estimate infiltration rate at each depth (Philip, 1987):

$$i = 0.5 \times S \times t^{-0.5} + A \qquad (2)$$

where:

i - infiltration rate [mm/h]

Measurements for each layer and replication were fitted according to this equation. An example of fitting for each layer (except middle of fragipan) for the third replication is presented in figure 2. The measurements were performed for two or two and half hours. During the fitting procedure it was found that the actual steady state was not reached during this time. Thus estimation was done beyond the measurement time, using equation (2), until the calculated infiltration rate was very close to steady state. In this case it was after eight hours. This cstimated value of hydraulic conductivity can be considered as a K_{sat}.

Philip equation parameters for each layer and each replication are presented in table 1. The parameters were estimated using the Marquard non-linear regression, with the use of the Statgraphics software. The Philip equation could not be used for the fragipan, because negative values of the A parameter were obtained. Thus infiltration rate curve reached negative values after a certain time of estimation. This is probably because the Philip equation is mathematical equation for infiltration into an infinitely deep homogeneous porous medium (Jury et al., 1991).

Tab. 1 Parameters for Philip equation and estimated infiltration rate.

		Parameters			Infiltration Rate *[mm/h]* after:			
Description	Rep.	S	A	R^2	2h	8h	CV [%]	Geom. Mean
							(for 8h)	(for 8h)
Surface (Ap)	1	3.87	20.47	99.86	21.8	21.1		
	2	16.34	31.35	99.61	37.1	34.2		
	3	19.09	23.55	99.34	30.3	26.9	23.9	26.9
	4	-	30.92					
Plow-pan (B)	3	10.42	5.81	98.55	9.5	7.6		
	4	11.79	10.40	99.86	14.6	12.5	34.0	9.8
Top of B horizon (Btg1)	2	12.31	10.72	99.91	15.1	12.9		
	3	7.93	3.47	99.93	6.3	4.9		
	4	6.11	6.27	99.85	8.4	7.3	49.1	7.7
Middle of B horizon (Btg2)	1	29.89	7.95	99.52	18.5	13.2		
	2	22.88	10.69	99.75	18.8	14.7		
	3	5.97	9.04	99.34	11.1	10.1		
	4	24.88	19.65	99.30	28.4	24.0	38.6	14.7
Top of fragipan (BTx)	1	12.26	1.05	99.78	5.4	3.2		
	2	15.32	0.98	99.77	6.4	3.7		
	3	6.04	1.53	98.90	3.7	2.6		
	4	6.59	3.93	99.14	6.3	5.1	29.1	3.5
Fragipan (IIBty)	1	12.25	-3.42		0.9	-		
	2	16.04	-3.33		2.3	-		
	3	26.25	-8.39		0.9	-		
	4	8.17	-1.46		1.4	0.0		-

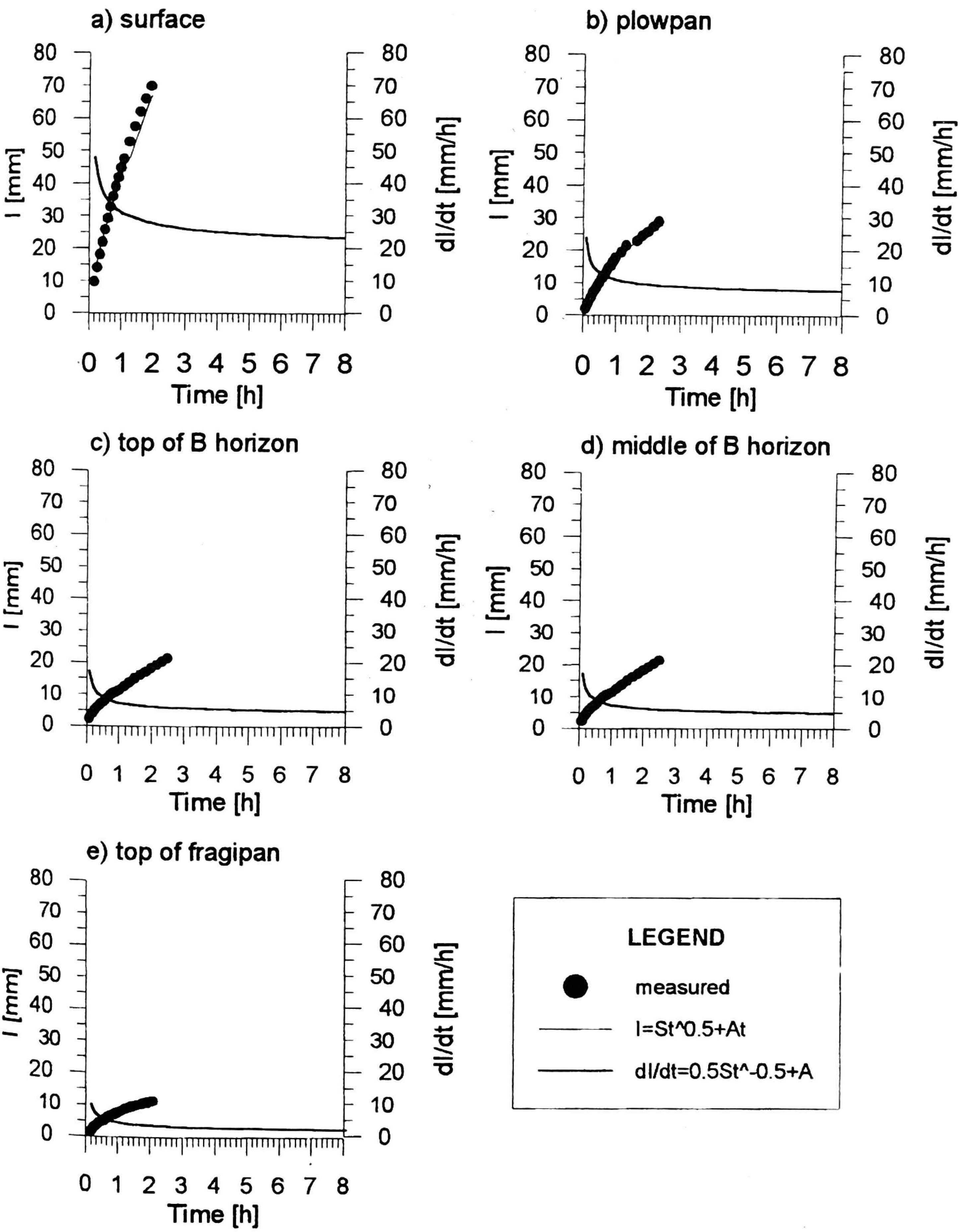

Fig. 2 An example of cumulative infiltration & infiltration rate for third replication

The low permeability of fragipan is increasing with depth and also non permeable palesol below fragipan is placed. When the wetting front reached paleosol, cumulative infiltration was very close to zero and the water was accumulated at the top of paleosol. Then horizontal flow, which was much slower than vertical flow, took place. The estimated K_{sat} values (infiltration rate after 8h) for each layer were averaged by geometric mean [Wojcik, 1993]:

$$\bar{x}_g = \left[\prod_{i=1}^{n} x_i \right]^{\frac{1}{n}} \qquad (3)$$

where:
x_i – individual measurement with number i
n – number of measurements
It was observed that the hydraulic conductivity is highly variable both in vertical and horizontal directions (Marcinek, 1992). This variability is difficult to interpretation and it does not link to known causes, and it can not be expressed an analytically. Thus it has to be express as a random variability. For this expression coefficient of variability *Cv* was calculated (Marcinek, 1992):

$$\mathbf{Cv} = \frac{\mathbf{S_t}}{\bar{\mathbf{x}}} \times \mathbf{100[\%]} \qquad (4)$$

where:
S_t – standard deviation
$\bar{\mathbf{x}}$ - mean

Summary and Conclusions

The research showed that the ponded infiltration technique can be applied for different depths in the soil profile. The advantage of the square frame infiltrometer was large area of vertical infiltration. Non-vertical infiltration appeared only in the relatively small area close to the frame. Thus relatively small variation of measured values was observed. Coefficient of variation values ranged from 23.9% for surface horizon to 49.1% for the top of B horizon. Using this method, values for estimation of K_{sat} for each separate layer (except the fragipan) were calculated. The algebraic Philip equation was suitable for the infiltration fitting and infiltration rate estimation. The fitting of Philip equation parameters is very accurate, because R^2 ranged in value between 98.55 % and 99.93 %. The sorptivity S and parameter A values depend on soil hydraulic properties and ranged from 3.87 to 29.89 [mm/h$^{0.5}$] (S) and from 0.98 to 31.35 [mm/h] (A). The highest K_{sat} is for surface (about 28 $^{mm}/_{h}$). For plowpan and top of B horizon K_{sat} contains between 8 - 10 $^{mm}/_{h}$. Next K_{sat} increases to about 15 $^{mm}/_{h}$ and for top of fragipan K_{sat} falls down to about 4 $^{mm}/_{h}$. For fragipan K_{sat} is probably close to zero. The fragipan was not considered with the Philip equation, because *A* parameter was negative for each replication. Thus the estimated K_{sat} reached a negative value after a certain time, which is physically impossible. The reason is that the Philip equation is a mathematical equation for infiltration into an infinitely deep homogeneous porous medium, whereas the fragipan and paleosol are not very porous. The sorptivity reached negative value for one case (4th replication for surface). It is not correct from theoretical point of view, because sorptivity can not be negative. Thus this case was excluded from further calculations. The large drop in conductivity at the fragipan confirms the necessity for tile drainage on this soil. The received results can be used for further study of water movement mechanisms into the soil profile and also for modeling of water and agrochemical flow to the drains. Also the problems where the Philip equation cannot be applied will be taken under consideration for further study.

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Summary

Hydraulic Conductivity of a Layered Soil Profile Measured by Ponded Infiltration Technique. Hydraulic conductivity is one of the fundamental soil properties, that determines the rate of water movement in the soil profile. The hydraulic conductivity is a significant factor for the design of drainage systems. Each equation for calculation of the required drain spacing includes conductivity coefficients for each separate soil layer.

The objective of this experiment was to measure the hydraulic conductivity of the four main horizons of the Clermont silt loam soil, to provide data for an ongoing drainage and water quality experiment. Equipment used for this method included: 1.2 m by 1.2 m metal frame, 200 liter barrel, float valve, indicator tube and stop watch. The equipment maintained a constant head of water within the frame, and the volume of water infiltrated was determined by measuring the volume of water remaining in the supply barrel. Saturated hydraulic conductivity was estimated when infiltration rates reached a steady state, usually within two hours. The experiment was done at six depths (5, 25, 30, 75, 110, 150 cm) in four different places in the field. Measured field data were statistically fitted to the Philip infiltration equation, which was also used to estimate Ksat of each depth. Saturated hydraulic conductivity ranged from 30 mm/h in the surface horizon to about 1 mm/h in the fragipan at 150 cm depth. The results confirm the necessity for tile drainage on this soil, and data will be used for modeling of water and agrochemical flow to the drains.

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