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ABSTRACT

A laboratory infiltrometer system was used to evaluate the infiltration process through reconstructed surface mine profiles. Six different profiles were subjected to constant simulated rainfall intensities for selected test conditions. Surface runoff rates were monitored and transient soil moisture contents in the profiles were measured with a gamma density gauge. Unsaturated hydraulic conductivity relationships were determined using Campbell's method and the "zero-flux" procedure. The infiltration process was modeled by the SCS curve number method, a form of Holtan's equation, the Green-Ampt model and Richards' equation. SCS curve numbers were determined by fitting the method to the observed results. Richards' equation gave very good estimates of the infiltration process through the spoil profiles, but was only slightly better than the Green-Ampt model. None of the models worked well for the profiles where macropore flow occurred through a two layer, topsoil-over-spoil system.

INTRODUCTION

One of the major components of the hydrologic cycle is infiltration. The ability of water to move through a soil profile has a direct effect on many of the components of the hydrologic cycle. In a previous paper (Ward et al., 1983a), results from an extensive series of infiltration experiments involving reconstructed profiles of surface mine spoil and topsoil material were presented. The purpose of this study was to evaluate four commonly used infiltration models in describing infiltration through reconstructed surface mine overburden and to broaden the limited data base of soil physical parameters which are essential in predicting infiltration in these media.

EXPERIMENTAL METHODS

Profile Construction and Characteristics

Surface mine spoils and soils were obtained from Peabody Coal Company's Alston Mine in Ohio County, KY. The spoil material was a mixture of grey and dark shale and sandstone. The topsoil material was a mixture of Belknap silt loam and Sadler silt loam. Physical and chemical properties of the spoil and soil materials are presented by Ward et al. (1983a).

The infiltrometer system incorporates two soil/spoil bins which have dimensions of 0.91 x 1.83 x 1.07 m deep. These bins were packed with soil and spoil materials to form profiles similar to those found in Western Kentucky. After initially filling the empty bins, new profiles were constructed by replacing the top 15 to 20 cm of material. Six profiles were constructed, three consisted entirely of spoil material, and three consisted of 15 cm of topsoil over spoil. The physical characteristics of the profiles are in agreement to those documented from field measurements in similar reconstructed media as discussed in Ward et al. (1983a). Profile bulk densities and changes in soil moisture content were measured with a Troxler two-probe gamma density gauge. Soil suction was measured with a series of tensiometers which were inserted horizontally into the sides of the bins at depth increments of 15 cm. A complete description of the instrumentation and the infiltrometer system is presented by Ward et al. (1981).

Infiltration Tests

The six soil/spoil profiles were constructed to evaluate the influence of rainfall intensity, initial moisture content, and bulk density on infiltration through the profiles. Initial soil/spoil moisture contents ranged from air dried to field capacity, and tests were conducted at rainfall intensities of 1, 2 or 3 cm/h.

At the beginning of each infiltration test, the gamma probe was used to determine initial moisture conditions in a profile. Scans were made every 2.54 cm down the profile in conjunction with the advances of the wetting front. Between movements, readings were taken at the same location every few minutes. Soil moisture contents behind the wetting front were determined by monitoring the grid locations above the wetting front every 30 to 60 min.

Accumulated infiltration was determined by taking the difference between the initial and final moisture contents for a profile as determined by the gamma probe. The infiltration rate during a test was determined by measuring runoff rates from the soil surface. This approach assumes that the rainfall rate is constant, that all the rainfall is applied to the soil surface, and that the surface storage is small. This approach also provided

another measurement of the accumulated infiltration volume.

The duration of each event was controlled so that the wetting front would pass beyond either the first or second level of tensiometers. The test durations ranged from 75 to 600 min depending on soil/spoil type and the density of the profile.

INFILTRATION MODELS

The SCS curve number method, a modified form of Holtan's equation, the Green-Ampt model, and Richards' equation were selected for evaluation because they are widely used, and have each been included in surface mine hydrology models. The Green-Ampt model (Green and Ampt, 1911) and Richards' equation (see, for instance, Smith and Woolhiser, 1971) are based on the physics of soil water movement, while the SCS curve number procedure (SCS, 1973) and Holtan's equation (Holtan, 1961) are empirical models which have parameters with no physical significance.

SCS Curve Number Method

This procedure was developed to predict surface runoff from small watersheds and was intended for use only where watershed data and daily rainfall records were available. The data used to develop the method were obtained from experimental plots for agricultural soils and agricultural land treatment measures (SCS, 1964). The expression for accumulated surface runoff, Q, is:

$$Q = \frac{(P - I_a)^2}{(P - I_a) + S} \quad \dots \dots \dots \dots \dots \dots \dots \dots [1]$$

where P is the accumulated rainfall, S is the potential maximum retention, and I_a represents initial abstractions. All quantities are expressed as inches or cm on the watershed.

The maximum potential storage is commonly related to the initial abstractions, I_a, by the relationship:

$$I_a = 0.2S \quad \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots [2]$$

To facilitate graphical representation of equation [1], S was then related to a curve number, CN, by the relationship:

$$CN = \frac{25400}{254 + S} \quad \dots \dots \dots \dots \dots \dots \dots \dots \dots [3]$$

where S is expressed in mm. Accumulated infiltration can then be termed as the difference between accumulated rainfall (P) and accumulated surface runoff (Q).

Holtan Model

Holtan (1961) and Holtan et al. (1967) proposed an empirical equation based on storage concepts for describing the infiltration process. The infiltration rate is expressed as a function of the available storage above an impeding layer and a final steady infiltration rate. Huggins and Monke (1967) modified Holtan's model to give:

$$f = f_c + a \left[(V_a - F)/V_p \right]^b \dots \dots \dots \dots \dots \dots \dots [4]$$

where f is the infiltration rate, f_c is final steady infiltration rate, F is the accumulated infiltration, V_a is the available storage ($F \leqslant V_a$) in the "control" zone and V_p is the total void volume of the "control" zone and where rates are expressed in cm/h or in./h and volumes are expressed in centimeters or inches. The "control" depth is defined as the depth of the impeding layer. An evaluation of the 'a', 'b', and 'f_c' values for four soils reported in the study by Huggins and Monke (1967) indicated that 'a' was 5 to 6 times 'f_c' and 'b' could be approximated by 0.65. Substituting these results into equation [4] gives:

$$f = f_c + 5f_c \left\{ (V_a - F)/V_p \right\}^{0.65} \dots \dots \dots \dots \dots [5]$$

where a is approximated as $5f_c$.

If the steady state infiltration rate is approximated by the field saturated hydraulic conductivity, K_{fs}, and total saturation is assumed to occur at a field saturated moisture content, Θ_{fs}, then equation [5] can be written as:

$$f = K_{fs} + 5K_{fs} \left\{ ((\Theta_{fs} - \Theta_i)L - F)/L\Theta_{fs} \right\}^{0.65}$$

$$\dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots [6]$$

where Θ_i is the initial moisture content and L is the depth of the control zone. The modified model is thus written in terms of soil physical characteristics.

To overcome problems associated with determining the control depth, a two stage solution of equation [6] was developed. The subscripts 1 and 2 denote the surface and subsurface layers, respectively. Definitions are the same as for the modified GAML model (described in the section immediately following) and reference should be made to Fig. 1. The two-stage solution is expressed as
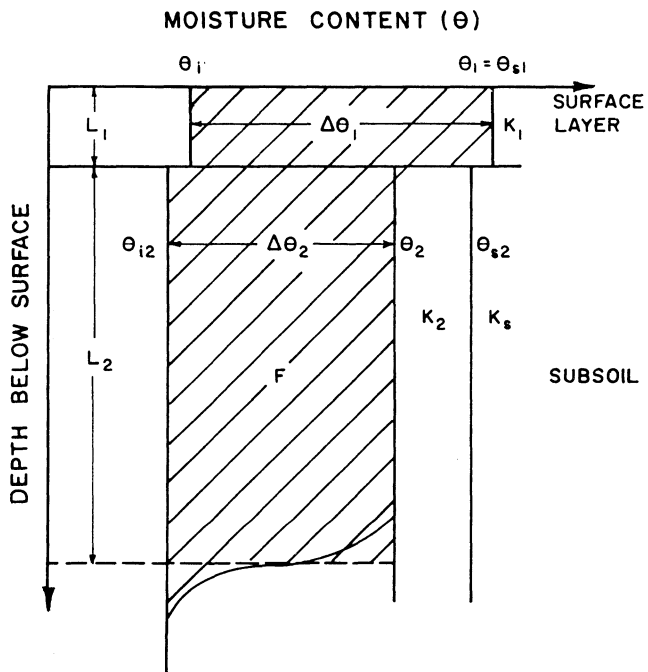

Fig. 1—Conceptual moisture profiles for derivation of modified GAML equation. (Source: Moore, 1981).

follows:

Stage 1:

$$f = K_1 + 5K_1 \left\{ ((\Theta_{s1} - \Theta_{i1})L_1 - F)/L_1\Theta_{s1} \right\}^{0.65}$$

$$\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots [7a]$$

if $f > i$, then $f = i$ (infiltration rate = rainfall rate)

Stage 2: The surface layer becomes saturated and, for $K_2 \leqslant K_1$:

$$f = K_2 + 5K_2 \left\{ \Delta\Theta_2 L_2 - F - \Delta\Theta_1 L_1)/L_2\Theta_{s2} \right\}^{0.65}$$

$$\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots [7b]$$

where $\Delta\Theta_2 = (\Theta_{s2} - \Theta_{i2})$ and $\Delta\Theta_1 = (\Theta_{s1} - \Theta_{i1})$. If $K_2 > K_1$, then $K_2 = K_1$.

This approximation allows infiltration into the unsaturated subsoil and assumes that the layer with the lower conductivity controls infiltration.

Green-Ampt Model

Green and Ampt (1911) developed an infiltration equation for ponded surfaces based on Darcy's Law and a capillary tube analogy. If the depth of surface ponding is negligible then this equation can be written as:

$$f = K_s \left[1 + \frac{S (\Theta_s - \Theta_i)}{F} \right] \dots\dots\dots\dots [8]$$

where S is the capillary suction at the wetting front, K_s is the saturated hydraulic conductivity, Θ_s is the saturated water content, f is the infiltrability, and the other terms are as previously defined.

Mein and Larson (1971) modified the Green-Ampt model to account for infiltration prior to surface ponding. Their two-stage infiltration model, which utilizes field saturation values of K and Θ, is described by two equations. Stage 1, up to the time to surface ponding, t_s, is described by:

$$F_s = \frac{S (\Theta_{fs} - \Theta_i)}{[i/K_{fs} - 1]} \dots\dots\dots\dots\dots\dots [9]$$

where F_s is the volume of infiltration at the time of surface ponding. At the time of surface ponding, the infiltration rate is equal to the rainfall rate and $t_s = F_{s/i}$. The second stage of infiltration, for $t > t_i$, is described by:

$$K_{fs} (t - t_s + t'_s) = F - S(\Theta_{fs} - \Theta_i) \ln \left[1 + \frac{F}{S(\Theta_{Fs} - \Theta)} \right]$$

$$\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots [10a]$$

where t'_s is the time required to infiltrate a volume equivalent to F_s under ponded surface conditions. Expressed in increment form:

$$K_{fs} \Delta t = \Delta F - S(\Theta_{fs} - \Theta_i) \ln \left[1 + \frac{\Delta F}{F_j + S (\Theta_{Fs} - \Theta_i)} \right]$$

$$\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots [10b]$$

where Δt is the time increment (= $t_{j+i} - t_j$), ΔF is the

incremental infiltration volume (= $F_{j+1} - F_j$), $t_j \geqslant t_s$ and subscript j refers to the time increment number.

Moore (1981) developed a solution of the GAML model for a two-layer soil profile. A conceptual soil profile for the procedure is illustrated in Fig. 1. If Darcy's law is applied to the system and the depth of ponding is negligible, f is determined as:

$$f = \frac{L + S_{w2}}{\dfrac{L_1}{K_1} + \dfrac{L_2}{K_2}} \quad \text{for } L \geqslant L_1 \dots\dots\dots\dots [11]$$

where S_{w2} is the capillary suction at the wetting front in the subsurface soil layer. At time, t, the volume of water infiltrated is:

$$F = L_1\Delta\Theta_1 + L_2\Delta\Theta_2 \dots\dots\dots\dots\dots [12]$$

By substituting $f = dF/dt$ into equation [1] and combining equations [11] and [12], the following expression for dF/dt is obtained:

$$\frac{dF}{dt} = \frac{L_1 + \dfrac{F - L_1\Delta\Theta_1}{\Delta\Theta_2} + S_{w2}}{\dfrac{L_1}{K_1} + \dfrac{F - L_1\Delta\Theta_1}{\Delta\Theta_2 K_2}} \dots\dots\dots\dots [13]$$

If equation [13] is integrated between the limits $t = t_1$ (F = F_1) and $t = t$, the following expression for the infiltration process is obtained:

$$F + (E - H)\ln \left(1 + \frac{F - F_1}{H} \right) = K_2 (t - t_1) + F_1$$

$$\text{for } F > F_1 \dots\dots\dots\dots\dots [14]$$

where $F = L_1\Delta\Theta_2(K_2/K_1)$; $H = \Delta\Theta_2 (L_1 + S_{w2})$; and $F_1 = L_1 \Delta\Theta_1$.

Equation [14] is the form of the Green-Ampt equation for single stage infiltration through the second layer of a two-layer system. For the GAML model for two stage infiltration through a two-layer system, the equations can be written in forms similar to equations [9] and [10].

$$F_s = \frac{H - E \left(\dfrac{i}{K_2} \right)}{\dfrac{i}{K_2} - 1} + F_1 \quad \text{for } F_s > F_1 \dots\dots\dots [15]$$

and

$$K_2 (t - t_s + t'_s) = (F - F_1) + (E + H) \ln \left[1 + \frac{F - F_1}{H} \right]$$

$$\text{for } F > F_1 \dots\dots\dots\dots\dots [16]$$

in which t'_s = the time required to infiltrate a volume equivalent to $F_s - F_1$ in Layer 2 under field saturated surface conditions (t'_s is obtained by substituting F_s for F in equation [14] and solving for $t'_s = (t - t_1)$. For computer applications, equation [16] is more easily

solved by rewriting it in incremental form similar to equation [10b]. That is, in the form,

$$K_2 \, \Delta t = \Delta F + (E - H) \, \ln \left[1 + \frac{\Delta F}{F_j + H - F_1} \right]$$

. . . . [17]

Equation [15] applies if F_s exceeds the storage volume in the surface layer. If $F_s < F_1$, equation [9] is used with the parameter estimates for the surface layer. The procedure is well-suited to solution by computer and the model described by Moore (1981) and Moore and Eigel (1981) was used in this study.

Richards' Equation

A computer model described by Moore and Eigel (1981) was used in this study to provide a finite difference solution of the one-dimensional form of Richards' equation for a non-swelling soil (for example, see Smith and Woolhiser, 1971):

$$\frac{\partial \Theta}{\partial t} = \frac{\partial}{\partial z} \left[K_s k_r(\psi) \frac{\partial \psi}{\partial z} \right] - \frac{\Delta [K_s k_r(\psi)]}{\partial z}$$

. . . . [18]

where Θ = volumetric moisture content
   K_s = saturated hydraulic conductivity
   k_r = relative hydraulic conductivity
   ψ = pressure head
   z = distance below the surface, and
   t = time.
A more convenient form of equation [18] is:

$$c \frac{\partial \psi}{\partial t} = \frac{\partial \psi}{\partial z} \left[K_s k_r(\psi) \frac{\partial \psi}{\partial z} \right] - \frac{\partial \, K_s k_r(\psi)}{\partial z}$$

. . . . [19]

where c is the moisture capacitance, $\partial \Theta / \partial \psi$. This equation has no exact general analytical solution. The equation is a second-order, non-linear partial differential equation for unsaturated flow in a porous media where air moves under negligible pressure gradients. An implicit Crank-Nicolson finite difference scheme was used to provide a solution to equation [19].

SOIL HYDRAULIC RELATIONSHIPS

Soil Water Release Curve

Soil-water release curves were determined based on a procedure described by Idike (1977). The relationship between the soil moisture content and the matric potential is given by the equation:

$$\psi = x \, \Theta^{-b}$$ . . . . [20]

where ψ is the matric potential (cm), Θ is the soil moisture content (cm³/cm³), x is the log-log plot intercept (cm), and b is the slope of the log-log plot. The procedure is only valid if the desorption data plot is a straight line on a log-log scale. To convert desorption data to adsorption data, the x-intercept is divided by 1.6 (Mein and Larson, 1971). The desorption data were obtained from the soil suction tensiometer data and the gamma probe data which were recorded at the beginning of each infiltration test, and from the "zero-flux" drying tests which were conducted to determine unsaturated hydraulic conductivity of the soil/spoil profiles.

Hydraulic Conductivity Relationships

Unsaturated hydraulic conductivity relationships were determined by Campbell's method (Campbell, 1974) and by the "zero-flux" procedure (Arya et al., 1975). Campbell's equation for estimating unsaturated hydraulic conductivity is as follows:

$$K = K_s (\Theta/\Theta_s)^{2b+3}$$ . . . . [21]

where K_s is the saturated hydraulic conductivity, K is the unsaturated hydraulic conductivity at the moisture content, Θ, and b is the slope term from equation [1]. The saturated moisture content, Θ_s, for the soil/spoil profiles is determined by the procedures used to determine soil moisture contents and bulk densities. Campbell's method assumes that the matric potential can be described by the relationship:

$$\psi = \psi_e \, (\Theta/\Theta_s)^{-b}$$ . . . . [22]

where ψ is the matric potential, ψ_e is the air entry water potential.

The "zero flux" procedure gives a simple numerical solution to Richards' equation (Skaggs et al., 1979) under the conditions where a field saturated soil is drying due to upward and downward movement of the soil water from a planar "zero flux" boundary. As the soil dries, this "zero flux" boundary moves down the soil profile thus maintaining the condition of no soil water movement across the boundary. The upward hydraulic conductivity at a depth z_a above the zero flux is given by the equation:

$$K(\psi_{z_a}) = \left[\int_{z_o}^{z_a} (\partial \Theta / \partial t) dz \right] / (\partial \phi / \partial z)_{z_a}$$

. . . . [23]

where ψ is the soil water potential, Θ the volumetric moisture content, t the time, and ϕ the total hydraulic head. To obtain solutions to this equation, the soil moisture content and soil suction profiles at several points in time after rainfall must be determined.

Zero flux drying cycle tests were conducted between several of the infiltration tests. Tensiometer readings were recorded 12 to 36 h after an infiltration test and then at intervals of 12 to 48 h thereafter. At each of these recording times, a scan was made of several of the gamma probe locations down to a depth of 30 to 45 cm. Readings were taken at depth increments of 2.5 cm within the profile with the gamma probe. These data were combined with the data describing the soil moisture content at the beginning of the infiltration tests.

An estimate of the field saturated hydraulic conductivity of a profile was made based on observed final steady state infiltration rates. Steady state infiltration tests ranged in duration from 4 to 6 days were conducted for two of the spoil profiles. The infiltration rate and soil moisture content of the profile were

measured periodically during these tests and the tests were continued until a steady state was observed for a period of at least 4 h.

Parameter Determination for the Modified GAML Procedure

Use of the procedure requires knowledge of the relationship between the hydraulic conductivity and capillary suction, the soil water characteristic relationship, and the porosity and depth of each layer. Using Campbell's Method, the suction at the wetting front can be determined by a procedure presented by Moore (1979). The suction at the wetting front in the GAML model was defined by Mein and Larson (1971) as:

$$S_w = \frac{\int_{K_{ri}}^{K_{rf}} S(K_r) \, dK_r}{K_{rf} - K_{ri}} \qquad [24]$$

where K_{rf} is the relative hydraulic conductivity at field saturation (K/K_s at Θ_{fs}%) and K_{ri} is the relative hydraulic conductivity at the initial moisture content Θ_i. By substituting equation [20] into equation [24], Moore (1979) obtained the following solution for S_w:

$$S_w = \frac{|\psi_e| \, (K_{rf}^a - K_{ri}^a)}{a(K_{rf} - K_{ri})} \qquad [25]$$

where $a = (b + 3)/(2b + 3)$ and ψ_e is the air entry water potential.

RESULTS

Parameter Estimation

Results of the analysis to determine soil water release curves and hydraulic conductivity relationships and corresponding parameter estimates are presented in Ward et al. (1983b).

Steady state infiltration tests for the spoil profiles 2 and 4 gave estimates of 0.22 and 0.04 cm/h, respectively, for the field saturated hydraulic conductivity. Dry bulk density and porosity were estimated for each soil layer using gamma-probe results and gravimetric soil water content. Field saturation for the two profiles was estimated as 91 and 85% of saturation. No steady state determination was made with profile 1 before the top portion was altered to form profile 3, although final infiltration rates for several of the tests indicated that 0.14 cm/h might be a good estimate. Steady infiltration tests for the three topsoil/spoil profiles were not conducted because final rates were controlled by the spoil layer. For these profiles relative conductivities were determined using Campbell's method and actual conductivities were determined by fitting these relationships to the results from the "zero-flux" tests as described in Ward et al. (1983b).

Experimental profiles with a surface layer of topsoil exhibited low infiltration capacity when subjected to simulated rainfall. To model this phenomenon, a shallow surface seal layer was specified as indicated in Table 1. Surface seal parameters were determined in the same way as for the soil layers previously described. Determination of field saturation in the topsoil layer of

TABLE 1.

Parameter	Units	Profile 1	Profile 2	Profile 3	Profile 4	Profile 5	Profile 6
No Seal							
Θ_{s1}	vol/vol	0.317	0.327	0.461	0.264	0.495	0.468
Θ_{s2}	vol/vol	0.333	0.333	0.333	0.333	0.333	0.333
K_1	cm/h	0.14	0.22	0.20	0.04	1.52	0.20
K_2	cm/h	0.22	0.22	0.22	0.22	0.22	0.22
S_{w1}	cm water	21.0	21.0	19.8	33.1	16.3	19.8
S_{w2}	cm water	21.0	21.0	21.0	21.0	21.0	21.0
L_1	cm	25.24	25.24	15.24	15.24	15.24	15.24
Surface Seal							
Θ_{s1}	vol/vol	*	*	0.461	*	0.495	0.468
Θ_{s2}	vol/vol			0.461		0.495	0.468
K_1	cm/h			0.06		0.06	0.06
K_2	cm/h			1.00		6.80	1.00
S_{w1}	cm water			19.8		16.3	19.8
S_{w2}	cm water			19.8		16.3	19.8
L_1	cm			0.40		0.40	0.40

*No results available.

the two layer profiles was complicated by the shallow depth of the topsoil layer, crack formation and surface sealing. An estimate of 90% of saturation was assumed for all three of the topsoil layers and field saturated hydraulic conductivity values were then calculated at these degrees of saturation using the Campbell equation results.

Infiltration Tests

Thirty four tests were conducted on the single layer spoil profiles and 24 tests were conducted on the two-layer topsoil over spoil profiles. Detailed accounts of the tests and corresponding results are presented in Ward (1981) and Ward et al. (1983a). The mean accumulated infiltration volume determined by the gamma probe procedure, for the spoil tests, was 0.53 cm less than the mean obtained with the runoff procedure. The difference in the means for the two-layers topsoil/spoil tests was only 0.37 cm, with the gamma probe again giving the lower mean value.

Infiltration Model Analysis

Curve numbers were determined for each test by using measured rainfall and runoff volumes and equations [1] and [3]. As the initial abstraction term in the SCS procedure includes surface storage, the runoff data results were used in the analysis. A regression analysis was conducted with the curve number results to develop a model for estimating curve numbers based on physical properties of a profile. Bulk density, total porosity, degree of saturation, and the initial volumetric soil moisture content (at the start of a test) were used in the analysis. The most statistically significant model can be expressed as:

$$CN = 145.8 - 231.2 \, (\Theta_s - \Theta_i) - 47.0(\Theta_i/\Theta_s)$$

$$\qquad [26]$$

where Θ_i is the initial soil moisture content (vol/vol) and Θ_s is the saturated soil moisture content or total porosity (vol/vol). The ($\Theta_s - \Theta_i$) term is a measure of the fillable porosity, and the (Θ_i/Θ_s) term is a measure of the degree of saturation. The coefficient of determination (r^2) of the equation is 0.83 and all the parameters are significant at

TABLE 2.

Profile	Test	Gamma probe, cm	Runoff data, cm	SCS* CN	SCS† CN	SCS, cm	Holtan, cm	GAML, cm	Richards', cm
1	1	5.89	5.80	73.0	68.6	4.88	7.49	5.08	—
	2	1.99	2.55	84.3	82.7	2.08	4.53	3.88	3.10
	3	2.47	3.04	79.4	84.8	1.62	4.18	3.47	2.74
	4	1.52	2.43	86.0	82.1	1.90	3.02	3.25	2.65
	6	1.84	2.35	85.9	84.8	1.66	2.16	3.04	2.09
	7	1.36	2.40	86.7	85.6	1.61	1.27	1.74	1.44
	10	1.28	2.44	83.2	84.5	1.46	2.23	1.90	1.64
2	5	4.91	5.35	61.0	57.8	4.72	5.49	3.88	—
	8	2.66	3.83	74.5	72.1	3.30	5.45	4.19	3.86
	9	1.58	2.10	88.1	79.8	2.10	2.51	2.14	1.98
	12	1.50	2.60	80.6	80.0	2.24	3.03	2.61	2.37
	14	2.50	2.50	84.8	78.3	2.25	3.89	3.03	2.73
	15	1.82	1.75	88.5	91.4	1.13	2.59	2.05	1.66
	17	1.97	2.38	8.39	79.6	2.06	3.13	2.56	2.33
	18	1.50	1.69	86.5	90.7	1.15	2.10	1.71	1.41
	20	2.56	3.87	75.4	80.5	2.47	3.73	3.14	2.89
	25	2.44	2.83	83.9	79.6	2.35	3.66	3.07	2.83
	26	1.80	2.38	83.1	82.2	1.83	2.61	2.24	2.04
	28	1.26	2.42	83.4	87.2	1.42	2.45	1.95	1.71
	30	3.65	3.04	77.4	80.5	2.13	3.27	3.25	2.92
	33	1.88	2.60	87.5	78.0	2.31	2.68	2.48	2.34
	34	1.24	1.19	95.3	87.8	1.35	1.73	1.68	1.44
3	11	8.06	8.65	50.6	44.8	9.01	6.05	4.82	—
	13	1.90	2.67	81.1	85.5	2.12	1.05	2.12	2.42
	16	2.60	2.39	83.1	79.0	2.88	1.50	2.37	2.75
	19	1.86	1.80	83.2	81.5	2.14	1.05	2.27	2.65
	21	1.87	2.37	76.0	79.0	2.61	1.39	2.38	2.64
	22	1.17	1.58	84.4	88.5	1.66	0.70	1.96	1.78
	23	0.91	1.56	85.3	89.1	1.64	0.68	1.91	1.85
	24	0.93	1.34	85.8	86.9	1.66	0.49	1.61	1.67
4	27	2.58	3.60	76.2	70.1	2.63	0.75	1.55	—
	29	1.33	1.72	84.8	78.8	1.85	0.93	1.54	1.47
	31	1.32	2.05	81.3	79.8	1.81	1.10	1.50	1.44
	32	0.87	1.51	86.6	88.9	1.09	0.70	0.87	0.73
	35	1.40	1.42	86.9	79.3	1.74	1.15	1.58	1.51
	36	0.65	0.96	90.3	88.0	1.08	0.72	0.80	0.73
	39	1.32	1.46	86.5	79.3	1.77	0.75	1.27	1.23
	40	0.91	1.47	88.3	89.0	1.11	0.85	0.96	0.90
	44	1.73	1.83	84.4	78.0	1.86	1.18	1.64	1.61
	46	0.89	0.90	91.4	88.0	1.13	0.78	0.99	0.88
	49	1.26	1.97	85.3	79.8	1.88	0.91	1.42	1.37
	51	0.82	1.35	88.1	89.9	1.05	0.64	0.80	0.74
5	37	8.35	10.04	18.8	40.1	8.58	5.86	8.98	—
	38	1.78	2.36	75.8	83.9	1.91	1.56	1.13	1.03
	41	3.28	3.61	67.7	72.7	2.97	2.54	1.95	1.98
	42	1.35	1.91	77.9	81.8	1.80	0.99	1.22	1.04
	43	2.54	3.13	65.9	75.1	2.80	2.47	1.89	1.93
	45	1.24	1.95	76.7	83.4	1.76	0.94	1.23	1.08
	48	1.95	2.13	61.0	79.3	1.85	1.79	1.22	1.06
	50	1.96	1.79	74.3	79.4	1.92	1.30	1.27	1.12
	54	3.48	3.86	64.7	72.7	3.00	2.14	4.17	4.10
	55	2.07	1.84	83.2	80.1	1.88	0.92	2.65	2.59
	58	3.49	3.77	73.7	71.04	3.13	2.11	4.34	4.35
	59	1.42	1.59	82.6	82.2	1.71	0.56	2.34	2.38
	47	2.83	3.33	58.5	68.6	2.96	2.81	1.94	1.94
6	52	5.70	6.09	55.4	47.8	6.70	2.74	3.40	—
	53	1.20	1.39	85.3	87.4	1.47	0.85	1.32	1.12
	56	2.27	2.44	75.4	75.6	2.53	1.42	1.89	1.71
	57	0.69	1.21	89.7	87.6	1.61	0.94	1.59	1.43
	60	1.90	1.90	82.0	78.1	2.36	1.31	1.90	1.65
	61	0.93	0.99	91.4	87.8	1.59	1.04	1.58	1.44

*Calculated from observed results.
†Calculated using equation [26].

the 99.99% level. Average Θ_i and Θ_s values for the top 15 cm of a profile were used in the analysis.

An analysis was conducted with equation [26] to determine how well it predicted the infiltration volumes for the 61 tests. Observed rainfall volumes were used in conjunction with curve numbers determined with equation [26]. Runoff and infiltration volumes were then calculated with equation [1]. The predicted infiltration results are presented in Table 2.

Observed versus predicted accumulated infiltration volume results for the analysis with the Holtan, Green-Ampt and Richards procedure are shown in Figs. 2 to 4, respectively. Stable solutions were not obtained with Richards' equation for the six air dried tests. For most of
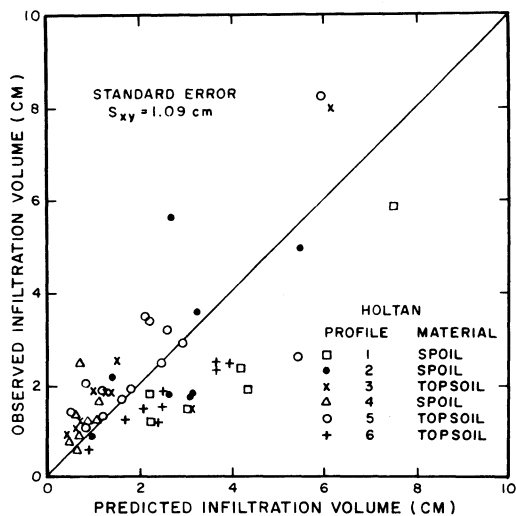
Fig. 2—Observed vs. predicted infiltration volumes. Holtan model results.
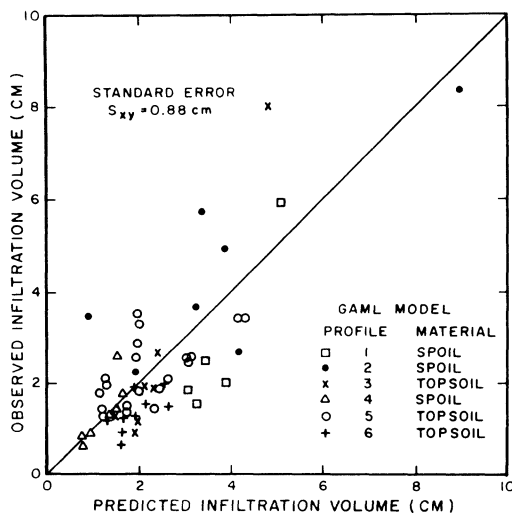

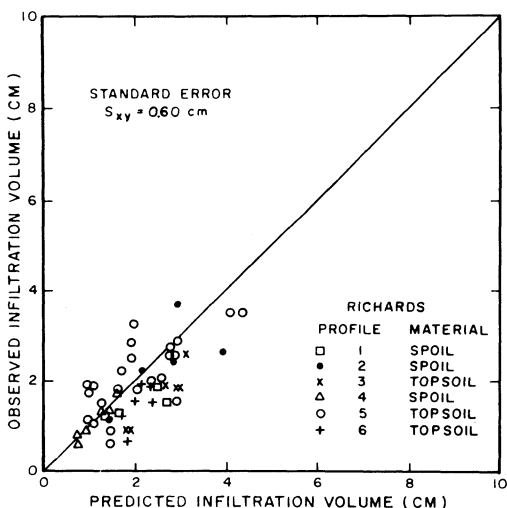Fig. 3—Observed vs. predicted infiltration volumes. GAML model results.

Fig. 4—Observed vs. predicted infiltration volumes. Richards equation results.
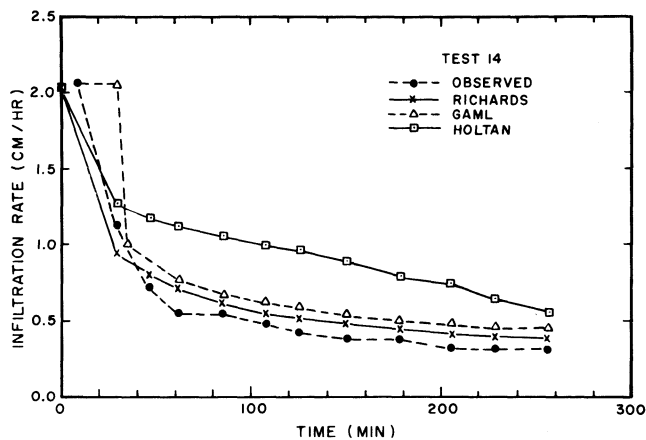

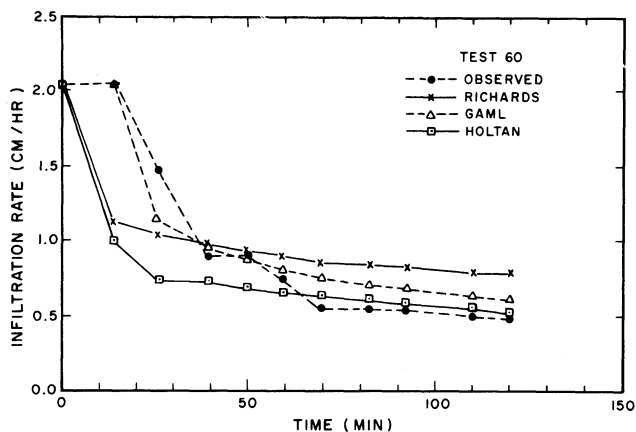Fig. 5—Typical transient infiltration rate estimates for a spoil profile.

Fig. 6—Typical transient infiltration rate estimates for a topsoil/spoil profile.

soil/spoil two layer profiles tests it was necessary to model surface sealing when using the Green-Ampt model and Richards' equation. Typical transient infiltration results for the three infiltration models are illustrated in Figs. 5 and 6. Steady state infiltration rate is a composite estimate of saturated hydraulic conductivity for each of the models presented. These estimates generally overpredicted infiltration over the time duration of tests conducted in this study. A detailed comparison between model results and observed infiltration versus time for each test are compiled by Ward (1981). Overall, the best results were obtained with Richards' equation. The Green-Ampt model gave very similar results to Richards' equation and both models worked well when micropore flow occurred. The performance of all three models for the tests conducted on the two-layer system was not very good. In Fig. 6, the Holtan model appears to provide the best description but in most of the tests the other models performed better. None of the models, however, gave good accounts of infiltration through the cracks in the topsoil layer.

Transient infiltration depth results are shown in Figs. 7 to 9. In Figs. 7 and 8, the ability of the Richards' equation to predict infiltration into the soil profiles is illustrated, while in Fig. 9 the inability of the procedure to model non-Darcian flow through the two layer system is illustrated.
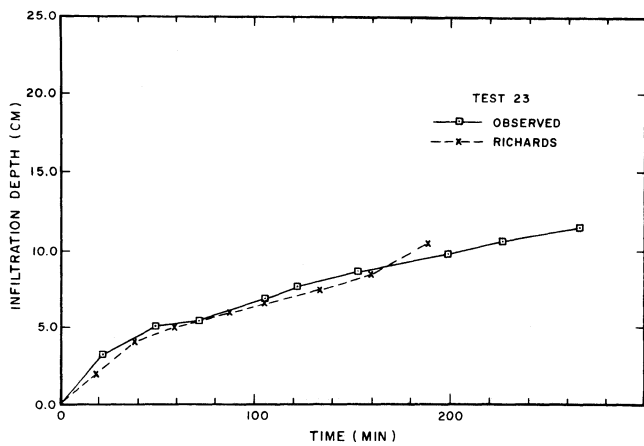
Fig. 7—Transient depth of infiltration results for test 29. (Spoil profile 4).
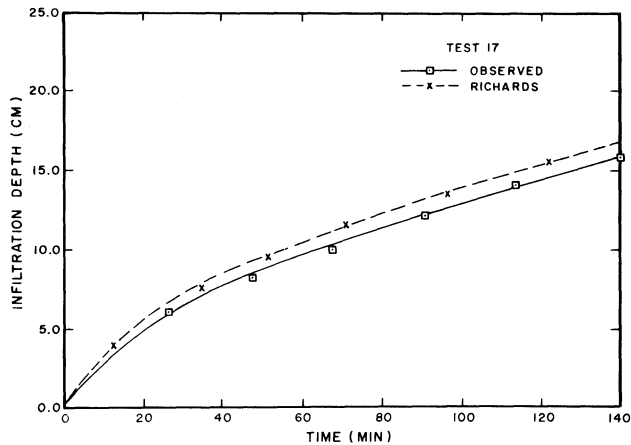

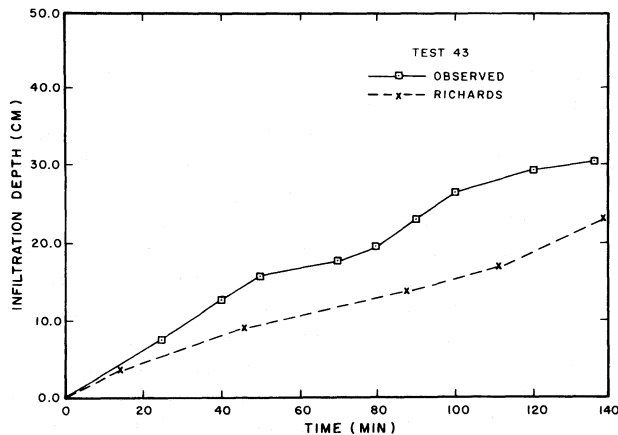Fig. 8—Transient depth of infiltration results for test 17. (Spoil profile 2).

Fig. 9—Transient depth of infiltration results for test 13. (Topsoil/spoil profile 5).

DISCUSSION

The runoff procedure for determining the accumulated infiltration volume consistently gave higher estimates of the infiltration volume. The higher estimates were attributed to the higher degree of surface storage accounted for by the procedure. Gamma probe measurements at a single scanning location will provide estimates which exclude the surface storage volume but accuracy is lost if the bulk densities and soil moisture values at this location are not representative of the average conditions in the profile. The runoff procedure provided a better estimate of transient infiltration rates and the gamma probe procedure gave more accurate estimates of the final accumulated infiltration volume. A detailed account of the measurement techniques used in this study is presented by Ward (1981).

The topsoil and spoil materials exhibited widely different infiltration characteristics. For the spoil material, infiltration primarily occurred as piston flow through the micropores of the profile. Macropore development in the spoil horizons was not observed. For the topsoil horizons, the infiltration process was very complex. Initially, infiltration occurred as channel flow through the macropores (large cracks). With time, the cracks at the surface would begin to seal and macropore flow would diminish. Infiltration rates would become much smaller and micropore flow through the surface seal and the walls of the macropores would be initiated. Because of the shallow depth of the topsoil horizon, the impeding soil sublayer influenced the infiltration process, making it difficult to quantify the different infiltration mechanisms in the topsoil horizon.

The SCS curve number model gave good estimates of the accumulated infiltration volume for each of the tests. The model was, however, fitted to each of the tests because of a lack of information on curve numbers for strip mine spoils and soils. The goodness of fit, therefore, is misleading. If a single curve number is used for tests with similar initial conditions, the goodness of fit is much worse. Caution should be used in attempting to apply these results in other situations. The analysis only suggests that the SCS procedure may show promise, provided a sufficient data base is developed over a wide range of material types, for such use.

The Holtan model gave poor descriptions of infiltration through the profiles. Performance of the method was slightly better for the topsoil/spoil profiles than for the spoil profiles. The modified model has the advantage over the original Holtan model in that it is based on physical and hydraulic parameters. The results indicated that, with some modifications, the performance of the model might be greatly improved. A wider base is, however, required to develop any further modifications. The current model cannot be recommended for use with surface mine spoils and soils from Western Kentucky.

The modified Green-Ampt model described infiltration moderately well for the spoil horizons and poorly for the topsoil/spoil horizons. Poor performance for the topsoil/spoil profiles was attributed to the difficulty in determining the model parameters and the non-piston type flow which occurred through this system. Parameters for all the horizons were related to field saturated conditions. For the spoil profiles, establishment of the parameters was straightforward although a knowledge of field saturation conditions was required. For the topsoil/spoil profiles, parameter determination was more complex. An alternative modeling approach (of the infiltration process) might have resulted in a better fit. The model appears suitable for application in any profile system where piston flow is perceived to occur. The modified model has the advantage over the original model in that it can be applied to a layered system.

The Richards equation numerical model gave the best description of infiltration through the different profiles. For the topsoil/spoil profiles, the model was not better than the GAML or Holtan models. For the spoil profiles, however, the model gave very good estimates of the infiltration process. A major disadvantage of the numerical algorithm used was that stable solutions were not obtained for the profiles with very dry initial moisture conditions. The modified GAML results were only slightly worse than the results obtained with the numerical model. It was felt, therefore, that for situations where piston type flow occurred, the modified GAML model could be used instead of Richards' equation.

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