Green-Ampt Infiltration Parameters from Soils Data

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Abstract: The analysis of approx 5,000 soil horizons indicated that Green and Ampt parameters (effective porosity, wetting front capillary pressure, and hydraulic conductivity) could not be developed based on phases of soil order or suborder. However, sets of average parameters are developed based on soil horizon or soil texture class, or both. A procedure for determining the Green and Ampt parameters based on soil properties utilizing the full spectrum of soil survey information is outlined.

Introduction

If physically based infiltration models are to be used in operational hydrology, procedures for estimating infiltration model parameters based on soil properties must be developed. Not only are improved procedures needed for estimating point soil parameters, but also methods are needed for quantifying the areal and temporal variation of the soil parameters (14).

The Green and Ampt infiltration model has been found to have wide applicability for modeling the infiltration process (10,15). The Green and Ampt rate equation is written as

$$f = K\left(1 + \frac{n\,\psi_f}{F}\right) \quad \text{(1)}$$

and its integrated form is

$$F - n\,\psi_f \ln\left(1 + \frac{F}{n\,\psi_f}\right) = Kt \quad \text{(2)}$$

in which K = hydraulic conductivity, in centimeters per hour; ψ_f = wetting front capillary pressure head, in centimeters; and n = available porosity which is calculated as the effective porosity, θ_e (total porosity, ϕ, minus residual saturation, θ_r), minus initial soil water content. Equation

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variables are f = infiltration rate, in centimeters per hour; F = infiltration amount, in centimeters; and t = time, in hours.

Application of the Green and Ampt infiltration model requires estimates of the hydraulic conductivity, K; effective porosity, θ_e; and wetting front capillary pressure head, ψ_f. Pioneering work on evaluating the Green and Ampt parameters was first reported by Bouwer (1). Additional work, relating the parameters to soil texture, has been reported by Clapp and Hornberger (7), Brakensiek, et al. (3), and McCuen, et al. (9). Since past work has used only a small portion of the available soil survey information, specifically soil texture, it is the purpose of this study to report on predicting the Green and Ampt parameters (K, θ_e, ψ_f) from soil properties utilizing the full spectrum of soil survey information.

The National Cooperative Soil Survey (a joint effort by cooperating Federal agencies, land grant universities, and other state and local agencies), uses a national system of soil classification (11,16). This system is based primarily on soil properties that can be observed in the field (e.g., texture) or inferred from other properties observable in the field (e.g., clay mineralogy). The differentiating soil properties are those that mainly affect plant growth and engineering use of the soil, such as particle size distribution, clay mineralogy, organic matter, soil temperature regime, soil moisture regime, carbonate content, and salt content.

Soil taxonomy is a hierarchy of six categories and each category includes a set of classes that are defined at about the same level. The most general definitions, with the fewest differentiating properties, are in the highest category, which consists of 10 orders. The most specific definitions, with the most differentiating properties, are in the lowest category, which is the soil series. There are more than 12,000 series. Soil series are the classes most commonly used to define and name map units in soil surveys, but classes in other categories are also used. The system is designed to facilitate both the interpretation of the soil data for practical application, and because it is national—the transfer of soil information from one location to another. A soil survey for an individual area is designed to meet certain objectives and satisfy the needs identified by local users and cooperating agencies. The distinguishing characteristics of soil surveys are summarized in Table 1.

A map unit delineated on a soil map is a unique soil area recognized in a particular soil survey area. Map units are named for the dominant soil or soils in the unit. The named soil can be at any of the categoric levels in the soil classification system. The more general the soil resource information needed, the higher the category used for the reference name.

Map unit delineations contain inclusions not identified in the map unit name. These units are named and identified by the taxonomic class they represent. Soils are natural bodies, and their properties have a characteristic natural scatter or variability. Because of this variability, certain properties may fall outside the precise limits defined for the named taxonomic class. Also, the map scale may be too small for precise mapping of a small area of these included soils. Map units are designed so that no more than about 15% of the unit consists of inclusions dissimilar enough that their use and management differ, and these inclusions are described in map unit descriptions. Generally, map units of soil surveys made in the U.S. are named for soil series. These units will provide the most precise soil-hydrologic data.

For order 5 soil surveys, the most distinguishable soil property is the taxonomic unit, specifically the soil order or suborder. For orders 2–4 soil surveys, the soil textures at various levels of detail are the most distinguishable soil properties. Also, for orders 2–4, information on horizon identification and depth and on mineralogy might be available. In addition to the information available for the higher order soil surveys, orders 1–2 soil surveys might have more specific information, such as

TABLE 1.—Criteria for Identifying Kinds of Soil Surveys[a]

Kinds of soil survey (1)	Kinds of map units (2)	Kinds of components (3)	Field procedures (4)	Appropriate scales for field mapping and published maps (5)	Minimum size delineation (6)
First order	mainly consociations and some complexes	phases of soil series	the soils in each delineation are identified by transection and traversing. Soil boundaries are observed throughout their length; air photo used to aid boundary delineation	1:12,000	1.5 acres
Second order	consociations, associations, and complexes	phases of soil series	the soils in each delineation are identified by transection and traversing; soil boundaries are plotted by observation and interpretation of remotely sensed data; boundaries are verified at closely spaced intervals	1:12,000–1:31,680	1.5 acres–10 acres
Third order	associations and some consociations and complexes	phases of soil series and soil families	the soils in each delineation are identified by transecting, traversing, and some observation and interpretation by remotely sensed data and verified with some observations	1:24,000–1:250,000	6 acres–640 acres
Fourth order	associations with some consociations	phases of soil families and subgroups	the soils of delineation representative of each map unit are identified and their patterns and composition determined by transecting; subsequent delineations are mapped by some traversing, by some observation, and by interpretation of remotely sensed data verified by occasional observations; boundaries are plotted by air photo interpretations	1:100,000–1:300,000	100 acres–1,000 acres
Fifth order	associations	phases of subgroups, great groups, suborders, and orders	the soils, their patterns, and their compositions for each map unit are identified through mapping selected areas (15 sq mile–25 sq mile) with first or second order surveys, or alternatively, by transection;	1:250,000–1:1,000,000	640 acres–10,000 acres

TABLE 1.—*Continued*

(1)	(2)	(3)	(4)	(5)	(6)
			subsequently, mapping is by widely spaced observations, or by interpretation of remotely sensed data with occasional verification by observation or traversing		

[a]Soil surveys of all orders require maintenance of a soil handbook (legend, mapping unit descriptions, taxonomic unit descriptions, field notes, and interpretations) and review by correlation procedures of the National Cooperative Soil Survey. Work plans for many survey areas list more than 1 order; the part to which each is applicable is delineated on a small scale map of the survey area.

Note: Undifferentiated groups may be used in any order with possible exception of first order. This is about the minimum size delineation for readable soil maps (i.e., 1/4 × 1/4 area)—see Table 2. In practice, the minimum size delineations are generally larger than the minimum shown. First order soil surveys are made for purposes that require appraisal of the soil resources of areas as small as experimental plots and building sites. Mapping scale could conceivably be as large as 1:1.

measured particle size information, measured soil water retention values, organic matter percentage, bulk density, and saturated hydraulic conductivity. Such detailed information might be available for higher order soil surveys; however, because of the large map scale, their usefulness might be extremely limited.

Sources of detailed soils information are the SCS Technical Service Center, the SCS National Soil Survey Laboratory, the state SCS offices, state universities (usually the soil science or agricultural engineering departments), and publications, such as Ref. 13.

Data Base

The data used in this study were from a comprehensive compilation of published soil water characteristic data, as of 1978, for approx 1,200 soils (5,000 horizons) covering 34 states (13). The distribution of the soils is shown in Fig. 1. Each soil set included at most: (1) Detailed profile descriptions; (2) particle size distribution; (3) bulk density; (4) total porosity; (5) clay mineralogy; (6) chemical data; and (7) five to 10 water retention valves covering a range of matric potentials from 160–15,300 cm.

The basic data covered most agricultural soils with the physical properties including a wide range of sand content (mean 56%, range 0.1%–99%), silt content (mean 26%, range 0.1%–93%), clay content (mean 18%, range 0.1%–94%), organic matter content (mean 0.66, range 0.1%–12.5%), and bulk density (mean 1.42 gm/cm^3, range 0.6–2.09). The soils included also both expanding (montmorillonite) and nonexpanding (kaolinite, illite, chlorite, and vermiculite) type clay minerals.

Analysis

It has been shown that the Green and Ampt parameters can be estimated from soil water data using the Brooks-Corey equation (Ref. 3). The Brooks and Corey equation (Ref. 4) is written as

$$S_e = \left(\frac{\psi_b}{\psi}\right)^{\lambda} \quad \text{in which} \quad S_e \text{ (effective saturation)} = \frac{\theta - \theta_r}{\phi - \theta_r} \qquad (3)$$

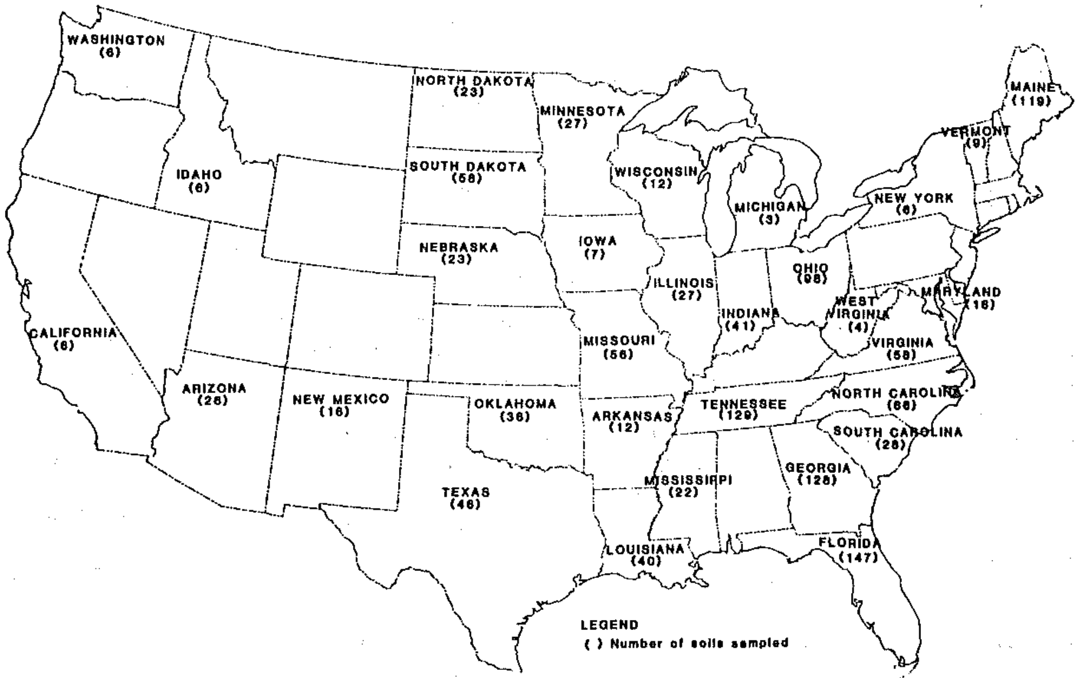

FIG. 1.—Distribution of Soils

in which θ = soil water content, in cubic centimeters per cubic centimeter; θ_r = residual saturation, in cubic centimeters per cubic centimeter; ϕ = total porosity, in cubic centimeters per cubic centimeter; ψ_b = bubbling pressure, in centimeters; ψ = capillary pressure, in centimeters; and λ = the pore-size distribution index.

The Green and Ampt parameters can be calculated from the estimated Brooks and Corey constants as follows: The wetting front capillary pressure term, ψ_f, is calculated by (2)

$$\psi_f = \frac{2\lambda + 3}{2\lambda + 2}\left(\frac{\psi_b}{2}\right) \qquad (4)$$

The effective porosity, θ_e, is calculated as

$$\theta_e = \phi - \theta_r \qquad (5)$$

in which ϕ = the total porosity, in cubic centimeters per cubic centimeter, and is calculated from bulk density and particle density; and θ_r = the residual soil-water content, in cubic centimeters per cubic centimeter. The Green and Ampt hydraulic conductivity, K, based on Bouwer's (4) findings that it is one-half the saturated hydraulic conductivity, is calculated as

$$K = \frac{K_s}{2} \qquad (6)$$

in which the saturated conductivity, K_s, is calculated by an equation (Ref. 5) derived by substituting the Brooks and Corey equation into the Childs, Collis-George permeability integral (6) given by

$$K_s = a\frac{\phi_e^2}{\psi_b^2}\left[\frac{\lambda^2}{(\lambda + 1)(\lambda + 2)}\right] \qquad (7)$$

in which a = a constant representing the effects of various fluid con-

TABLE 2.—Green and Ampt Parameters According to Soil Texture Classes and Horizons

Soil texture class (1)	Horizon (2)	Sample size (3)	Total porosity, ϕ, in cubic centimeters per cubic centimeters (4)	Effective porosity, θ_e, in cubic centimeters per cubic centimeters (5)	Wetted front capillary pressure, ψ_f,[a] in centimeters (6)	Hydraulic conductivity, K,[b] in centimeters per hour (7)
Sand[c]		762	0.437 0.374–0.500[d]	0.417 (0.354–0.480)	4.95 (0.97–25.36)	11.78
	A	370	0.452 (0.396–0.508)	0.431 (0.375–0.487)	5.34 (1.24–23.06)	
	B	185	0.440 (0.385–0.495)	0.421 (0.365–0.477)	6.38 (1.31–31.06)	
	C	127	0.424 (0.385–0.463)	0.408 (0.365–0.451)	2.07 (0.32–13.26)	
Loamy sand		338	0.437 (0.363–0.506)	0.401 (0.329–0.473)	6.13 (1.35–27.94)	2.99
	A	110	0.457 (0.385–0.529)	0.424 (0.347–0.501)	6.01 (1.58–22.87)	
	B	49	0.447 (0.379–0.515)	0.412 (0.334–0.490)	4.21 (1.03–17.24)	
	C	36	0.424 (0.372–0.476)	0.385 (0.323–0.447)	5.16 (0.76–34.85)	
Sandy loam		666	0.453 (0.351–0.555)	0.412 (0.283–0.541)	11.01 (2.67–45.47)	1.09
	A	119	0.505 (0.399–0.611)	0.469 (0.330–0.608)	15.24 (5.56–41.76)	
	B	219	0.466 (0.352–0.580)	0.428 (0.271–0.585)	8.89 (2.02–39.06)	
	C	66	0.418 (0.352–0.484)	0.389 (0.310–0.468)	6.79 (1.16–39.65)	
Loam		383	0.463 (0.375–0.551)	0.434 (0.334–0.534)	8.89 (1.33–59.38)	0.34
	A	76	0.512 (0.427–0.597)	0.476 (0.376–0.576)	10.01 (2.14–46.81)	
	B	67	0.512 (0.408–0.616)	0.498 (0.382–0.614)	6.40 (1.01–40.49)	
	C	47	0.412 (0.350–0.474)	0.382 (0.305–0.459)	9.27 (0.87–99.29)	
Silt loam		1,206	0.501 (0.420–0.582)	0.486 (0.394–0.578)	16.68 (2.92–95.39)	0.65
	A	361	0.527 (0.444–0.610)	0.514 (0.425–0.603)	10.91 (1.89–63.05)	
	B	267	0.533 (0.430–0.636)	0.515 (0.387–0.643)	7.21 (0.86–60.82)	
	C	73	0.470 (0.409–0.531)	0.460 (0.396–0.524)	12.62 (3.94–40.45)	
Sandy clay loam		498	0.398 (0.332–0.464)	0.330 (0.235–0.425)	21.85 (4.42–108.0)	0.15
	A	—[e]	— —	— —	— —	
	B	198	0.393 (0.310–0.476)	0.330 (0.223–0.437)	26.10 (4.79–142.30)	
	C	32	0.407 (0.359–0.455)	0.332 (0.251–0.413)	23.90 (5.51–103.75)	
Clay loam		366	0.464 (0.409–0.519)	0.309 (0.279–0.501)	20.88 (4.79–91.10)	0.10
	A	28	0.497 (0.434–0.560)	0.430 (0.328–0.532)	27.00 (6.13–118.9)	
	B	99	0.451 (0.401–0.501)	0.397 (0.228–0.530)	18.52 (4.36–78.73)	
	C	55	0.452 (0.412–0.492)	0.400 (0.320–0.480)	15.21 (3.79–61.01)	
Silty clay loam		689	0.471 (0.418–0.524)	0.432 (0.347–0.517)	27.30 (5.67–131.50)	0.10
	A	65	0.509 (0.449–0.569)	0.477 (0.410–0.544)	13.97 (4.20–46.53)	
	B	191	0.469 (0.423–0.515)	0.441 (0.374–0.508)	18.56 (4.08–84.44)	
	C	39	0.475 (0.436–0.514)	0.451 (0.386–0.516)	21.54 (4.56–101.7)	
Sandy clay		45	0.430 (0.370–0.490)	0.321 (0.207–0.435)	23.90 (4.08–140.2)	0.06
	A	—	— —	— —	— —	
	B	23	0.435 (0.371–0.499)	0.335 (0.220–0.450)	36.74 (8.33–162.1)	
	C	—	— —	— —	— —	
Silty clay		127	0.479 (0.425–0.533)	0.423 (0.334–0.512)	29.22 (6.13–139.4)	0.05
	A	—	— —	— —	— —	
	B	38	0.476 (0.445–0.507)	0.424 (0.345–0.503)	30.66 (7.15–131.5)	
	C	21	0.464 (0.430–0.498)	0.416 (0.346–0.486)	45.65 (18.27–114.1)	
Clay		291	0.475 (0.427–0.523)	0.385 (0.269–0.501)	31.63 (6.39–156.5)	0.03
	A	—	— —	— —	— —	
	B	70	0.470 (0.426–0.514)	0.412 (0.309–0.515)	27.72 (6.21–123.7)	
	C	23	0.483 (0.441–0.525)	0.419 (0.294–0.544)	54.65 (10.59–282.0)	

[a]Antilog of the log mean and standard deviation.
[b]Values for Rawls, et al. (13).
[c]Values for the texture class.
[d]Numbers in ( ) ± one standard deviation.
[e]Insufficient sample to determine parameters.

stants and gravity. The constant a equals 270 cm^3/sec according to Brutsaert (5).

The Brooks and Corey equation was fitted to the water retention data using pattern search optimization. Only the optimizations which produced a correlation coefficient significant at the 95% level were used. The Green and Ampt parameters were calculated from the Brooks and Corey parameters using Eqs. 4–7. Checking the saturated hydraulic conductivities derived from Eq. 7 with those reported in Rawls, et al. (13), we find that Eq. 7 produced saturated hydraulic conductivities that were approximately one order of magnitude too high; therefore, we calibrated the constant in Eq. 7 to the Rawls, et al. (13) 11 soil textures. This fitting produced a value of the a constant equal to 21.0 cm^3/sec.

The data included six of the 10 soil orders and 17 of the 49 soil suborders. Analysis of the data indicated that mean Green and Ampt parameter values were not significantly different for soil orders and suborders, thus we concluded that use of the Green and Ampt infiltration model is inappropriate for the Order 5 soil surveys.

Analysis of the data according to soil texture classes, horizon, and clay mineralogy indicated that soil texture classes were the most significant discriminators of the Green and Ampt parameters. Also, a further division according to major horizons (A, B, C) yielded further classification accuracy. Clay mineralogy was not found to be significant. The mean parameter values and standard deviations are summarized in Table 2 for the 11 USDA soil texture classifications and major horizons. The values given in Table 2 can be used when applying the Green and Ampt infiltration model using orders 2–4 soil surveys.

We considered using more detailed soil information, such as particle size distribution, organic matter, bulk density, and 1/3 and 15 bar moisture retention values, to make better estimates of the Green and Ampt parameters (ψ_f, θ_e, K) than just average values according to soil texture class and horizon. First, we attempted to relate the Green and Ampt parameters to the particle size distribution, organic matter, and bulk density using regression analysis; however, these relationships yielded correlation coefficients of approx 0.6–0.75, which we felt were not adequate for predictive purposes. Therefore, we used the approach presented by Gupta and Larson (8), and Rawls, et al. (12,13) in which the soil water retention values for −0.1, −0.2, −0.33, −0.60, −1.0, −2.0, −4.0, −10.0, and −15.0 bar matric potentials were related to the particle size, percentages, organic matter, bulk density, and measured soil water content at specific matric potentials. Depending upon which parameters were included in the relationship, this approach predicted soil water retention at specific matric potential with a correlation coefficient ranging between 0.80 and 0.98. A sensitivity test on clay, sandy loam, and silt loam textures was performed utilizing various combinations of the 10 water retention matric potential values. We concluded that for the purpose of determining the Green and Ampt parameters, only six points on the water retention matric potential curve are needed. The best combination of points is the 0.1, 0.33, 1, 4, 10, and 15 bar water retentions.

Conclusion

Appropriate procedures for determining Green and Ampt infiltration parameters (effective porosity, wetting front capillary pressure, and hydraulic conductivity) could not be developed for order 5 soil surveys. However, for orders 1–4 soil surveys, the methods for determining the Green and Ampt parameters, ranked according to accuracy, are:

1. Fit the Brooks and Corey equation to measured water retention matric potential data and determine the Green and Ampt parameters from the Brooks and Corey parameters. This probably is the most expensive and time-consuming approach.
2. Fit the Brooks and Corey equation to published water retention matric potential data obtained form literature sources, such as Rawls, et al. (13), and determine the Green and Ampt parameters from the Brooks and Corey parameters.
3. Predict the moisture tension curve based on particle size distribution, organic matter, bulk density, and either 1/3 or 15 bar water content, or both, using appropriate set of equations given in Rawls, et al. (13), or Gupta and Larson (8) for the 0.1, 0.33, 1, 4, 10, and 15 bar moisture values. Fit the Brooks and Corey equation to the water retention matric potential curve and then predict the Green and Ampt parameters from the Brooks and Corey parameters.
4. Estimate the parameters based on profile horizon and soil texture classes (Table 2).
5. Estimate the parameters based on soil texture classes (Table 2).

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