ESTIMATION OF GREEN-AMPT CONDUCTIVITY PARAMETERS: PART I. ROW CROPS

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ABSTRACT. *Parameterization is the key factor affecting the implementation of most infiltration models. For the successful application of the Green-Ampt equation in the Water Erosion Prediction Project (WEPP) model, procedures for estimating the effective hydraulic conductivity (K_e) must be developed. The objective of this study was to identify the major variables which affect K_e under row-cropped conditions and to develop statistical equations to quantify these relationships for use in WEPP. A total of 328 plot-years of data from natural runoff plots from eight sites was used to develop equations for estimating temporal variability of K_e under row-cropped conditions. The average period of record for each crop management system was approximately nine years, during which an average of 96 storm events was selected for each treatment. Crops included corn, cotton, oats, soybeans, and potatoes. Measured soil, climate, slope, and crop management information was used to build all of the WEPP input files. An optimization program was written to determine K_e for every selected event for which measured and predicted runoff volumes matched. Correlation analyses showed that storm rainfall, total effective surface cover, and their cross-product were strongly related to the optimized K_e. An interactive term consisting of soil properties, storm rainfall, and effective surface cover was developed and used for K_e prediction for row-cropped conditions. The r^2 for model predicted total runoff of the selected events versus the measured was 0.94 and the slope of regression was 1.01. Model efficiencies for individual storm runoff predictions averaged 0.66. The results also showed that seasonal variations of K_e and runoff were adequately represented.*

Keywords. *WEPP, Green-Ampt equation, Hydraulic conductivity, Runoff prediction, Crop management.*

One of the greatest challenges in the general application of infiltration models is parameter characterization and estimation. Generally, model parameters are either estimated from theoretical considerations or calibrated from measured data. The latter approach is often taken because of high spatial and temporal variabilities of parameters under natural conditions.

The Water Erosion Prediction Project (WEPP) model uses the Green-Ampt equation (Green and Ampt, 1911) to calculate infiltration. Chu (1978) developed a procedure for applying this equation to unsteady rainfall conditions. The general form of the equation is:

$$f = K_e(1 + N_s/F) \quad (1)$$

where

- f = infiltration rate (mm/h)
- K_e = effective hydraulic conductivity (mm/h)
- F = accumulated infiltration (mm)
- N_s = effective matric potential (mm) and is calculated by:

$$N_s = (\eta_e - \theta_i)\Psi_f \quad (2)$$

where

- η_e = effective porosity
- θ_i = initial water content (mm^3/mm^3)
- Ψ_f = average wetting front capillary potential (mm)

The application of this model requires estimates of the two key parameters, K_e and Ψ_f. Ψ_f can be calculated from effective porosity and soil sand and clay contents (Brakensiek, 1977; Rawls et al., 1989).

However, K_e is known to depend not only on fallow soil conditions but also on residue management practices (Rawls et al., 1991; Wischmeier, 1966). Bare soil surfaces exposed to rain drop impact are susceptible to soil sealing and crusting. It is known that the hydraulic conductivity of soil surface seals is several orders less than that of underlying uncrusted soils (McIntyre, 1958; Shainberg and Singer, 1986). Therefore, quantifying crust formation and its effect on K_e is of great importance in runoff prediction. Risse et al. (1995) recently developed the following equation to compute effective hydraulic conductivity for bare conditions (K_{bare}) by simulating the effect of crusting and tillage on K_e under fallow conditions:

$$K_{bare} = K_b\{CF + (1 - CF)\exp[-C_s \times E_a(1 - rr/4)]\} \quad (3)$$

where

- K_b = baseline hydraulic conductivity (mm/h)
- CF = crust factor
- C_s = structural stability factor in m^2/J that can be estimated from soil properties (Risse et al., 1995)
- E_a = cumulative kinetic energy of rainfalls since last tillage in J/m^2

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rr = random roughness (cm)

In this equation, K_b is defined as the maximum hydraulic conductivity which occurred under freshly tilled and noncrusted conditions. K_{bare} decreases exponentially as E_a increases. Rapidity of the decrease depends on C_s. CF, defined as a ratio of effective conductivity of two-layer system (including surface crust) to saturated subcrust conductivity, is calculated by Rawls et al. (1990):

$$CF = C_{ps}/(1 + \Psi_i/L) \quad (4)$$

where

C_{ps} = correction factor for partial saturation of the subcrust soil

Ψ_i = steady state capillary potential at the crust/subcrust interface (cm)

L = wetted depth (cm) that can be estimated by dividing the accumulated infiltration by available porosity (total porosity minus initial soil moisture)

They also derived the following equations for estimating C_{ps} and Ψ_i:

$$C_{ps} = 0.736 + 0.0019\ (\%\ \text{sand}) \quad (5)$$

$$\Psi_i = 45.19 - 46.68 \times C_{ps} \quad (6)$$

Surface cover is one of the most effective means in dissipating raindrop impact energy and reducing soil crusting. Surface runoff can be dramatically reduced when crusts are controlled by surface cover. Analyses of natural rainfall plot data showed that the runoff from continuous conventional corn was more than 50% less than that from companion fallow plots (Wischmeier, 1966). Mannering and Meyer (1963) and Taylor et al. (1964) reported that surface runoff was reduced tremendously by residue mulch. On the other hand, the reported degree of increase in infiltration rate due to surface cover varies significantly between studies (Meyer et al., 1970; Lattanzi et al., 1974; Gilley et al., 1986), partially due to the fact that the degree of infiltration improvement depends on soil properties. For easily crusted soils, the improvement would be more pronounced. Crop management and tillage systems were also reported to affect infiltration by altering soil surface conditions and soil physical properties (Dickey et al., 1984).

Canopy cover is less effective in reducing runoff than residue cover due to canopy height effect (Wischmeier and Smith, 1978; Wischmeier, 1975; Khan et al., 1988). Khan et al. (1988) found runoff volume was significantly reduced as canopy and residue cover increased, and was increased when canopy height increased. For accurate simulation of the effect of canopy cover on runoff production, the impact of canopy height must be considered.

A few studies have been explicitly conducted to examine the interactive effect of surface cover and rainfall characteristics on water infiltration. Rawls et al. (1991) conducted a field rainfall simulation study during a growing season and found that there existed a positive interaction between rainfall intensity and surface cover. Based on analyses of the natural rainfall plot data, Wischmeier (1966) found the greatest gain in infiltration occurred with large rainstorms if residue was left on the soil surface. These findings indicate the importance of the interaction between rainfall properties and surface cover in runoff prediction under cropped conditions.

Several equations have been proposed to estimate hydraulic conductivity to account for the effect of surface cover. Freebairn et al. (1989) optimized K_e by fitting the Green-Ampt equation to measured infiltration data over a series of storms during a growing season. They found the mean optimized K_e value was statistically related to surface conditions of the soil by:

$$K_e = 51 - 9.2R_a + 15SC \quad (7)$$

where R_a is the cumulative rainfall since last tillage (mm), and SC is the surface cover expressed as a decimal. Van Doren and Allmaras (1978) proposed the following untested exponential relationship to estimate the transient hydraulic conductivity, K_t, during a single storm for the different surface conditions:

$$K_t = K_i \exp[-C_s(1 - SC)E_a] \quad (8)$$

in which K_i is similar to K_b in equation 3 and is defined as hydraulic conductivity immediately after tillage, and the other variables are as defined above. A similar exponential function was proposed for use during a single storm by Brakensiek and Rawls (1983):

$$K_t = K_f + (K_b - K_f)\exp[-C_s(1 - SC)(1 - rr/4)E_a] \quad (9)$$

where K_f is the final hydraulic conductivity during a storm.

Based on 35 years of field-plot studies at 47 research stations in the United States, Wischmeier (1966) concluded

Table 1. Site and crop management descriptions

Site	Crop Management	Number of Rep-licates	Years	Number of Events Used
Hollysprings, Miss.	a. fallow	2	1961-1968	208
Slope: 0.05 m/m	b. cont. corn, spring TP*	2	"	163
Size: 4 × 22.1 m				
Madison, S.D.	a. fallow	3	1962-1970	59
Slope: 0.06 m/m	b. cont. corn, spring TP	3	"	48
Size: 4 × 22.1 m	c. cont. corn, no TP	3	"	50
	d. cont. oats	3	1962-1964	15
Morris, Minn.	a. fallow	3	1962-1971	67
Slope: 0.06 m/m	b. cont. corn, fall TP	3	"	67
Size: 4 × 22.1 m				
Presque Isle, Maine	a. fallow	3	1961-1965	65
Slope: 0.08 m/m	b. cont. potato	3	"	64
Size: 3.7 × 22.1 m				
Watkinsville, Ga.	a. fallow	2	1961-1967	147
Slope: 0.07 m/m	b. cont corn, spring TP	2	"	97
Size: 4 × 22.1 m	c. cont. cotton, spring TP	2	"	112
Bethany, Mo.	a. fallow	1	1931-1940	109
Slope: 0.07 m/m	b. cont. corn, spring TP	1	"	112
Size: 4.3 × 21.3 m				
Geneva, N.Y.	a. fallow	1	1937-1946	97
Slope: 0.08 m/m	b. summer fallow, winter rye	1	"	77
Size: 1.8 × 22 1 m	c. cont. soybean, spring TP	1	"	45
Guthrie, Okla.	a. fallow	1	1942-1956	170
Slope: 0.08 m/m	b. cont. cotton, spring TP	1	"	140
Size: 1.8 × 22.1 m				

* Turn plow.

that the infiltration rate was influenced more by surface conditions and management than specific soil type. Thus, the parameterization of K_e for different surface conditions is extremely important for the successful application of the Green-Ampt equation. The purpose of this article was to identify the major variables which affect K_e adjustment under row-cropped conditions and to develop statistical relationships for predicting K_e under those conditions.

MATERIALS AND METHODS

RUNOFF DATA

Site and crop management descriptions are given in table 1. Data from 41 natural rainfall plots from eight sites were selected from the repository of soil loss data located at the National Soil Erosion Research Laboratory. To quantify the effect of surface cover on hydraulic conductivity under cropped conditions, the existence of companion fallow plots was an essential criterion in site selection. Sites/plots with contoured tillage were excluded to minimize the surface storage induced bias in K_e optimization. In addition, soil, crop, and climate types were considered to obtain a range of environmental conditions represented in the study. The average period of records for each crop management system was approximately nine years. A total of 328 plot-years of data with 1912 measured runoff values was used. Runoff plots for each crop management system were replicated at five of the eight sites.

The WEPP management input file for each crop was compiled according to the recorded experimental data from the site records. Plant growth parameters in WEPP were calibrated to obtain realistic above ground biomass, either in comparison to recorded biomass data if it existed or reasonable biomass production levels for the site if the data did not exist. The crops included corn, cotton, soybeans, oats, and potatoes (table 1). Continuous conventional management was practiced on all crops. Except for the Bethany and Presque Isle sites, residue was left on the ground at harvest and turn-plowed in either the fall or the next spring. Common conventional tillage tools such as moldboard, disk, and harrow were utilized for seedbed preparation.

In the WEPP climate input file, the four most sensitive parameters (daily rainfall amount, rainfall duration, time to maximum intensity, and ratio of mean to maximum intensity) were determined from breakpoint data for each individual storm to minimize the effect of input parameter-associated errors on K_e optimization. Remaining parameters, including solar radiation, wind velocity and direction, and dew point temperature, were generated by CLIGEN (climate generator, Nicks et al., 1993) for each site using the measured daily maximum and minimum temperatures and rainfall amount. Plots were standard USLE natural rainfall plots, each approximately 22 m long and 4 m wide, except for the Geneva and Guthrie sites where a plot width of 1.8 m was used. Slopes on all plots were nearly uniform and ranged from 0.05 to 0.08 m/m. In the WEPP soil input file, the baseline hydraulic conductivity (K_b) for the infiltration layer of the top 20 cm was obtained by optimizing equation 3 for the fallow plot runoff data, and the results are given in table 2. This parameter is closely related to or similar in value to the saturated conductivity of the soil under freshly tilled and noncrusted field conditions. But it is not the same as the saturated conductivity of the soil since errors, such as those in representing rainfall breakpoint data and in predicting soil matric potential, may bias K_e optimization. The saturated hydraulic conductivities for the underlying soil layers, which are used in water balance calculations, were calculated using the equations developed for the Erosion Productivity Impact Calculator (EPIC) model (Sharpley and Williams, 1990). Other parameters such as sand and clay contents, percent organic matter, and cation exchange capacity were obtained from the available measured data. To ensure adequate root growth and its impact on the water balance component, the thickness of soil profile used on each site was greater than 1.5 m. Detailed soils information is presented in table 2.

The storm events for each crop management system were carefully selected based on data quality (table 1). Only events with a daily minimum temperature above 0° C, measured rainfall with breakpoint data, and reliable runoff data were used. Events were excluded if there were apparent errors in the data, such as those for which the measured runoff volume was greater than rainfall amount, or where the differences in runoff among replicates seemed to indicate a measured error. The events with short duration (normally < 24 h) were preferred, while rainfall events which occurred over multiple days were excluded. Six to 12 of the largest storms with no measured runoff were included to reduce bias in the event file. The averaged runoff volumes from replicate plots were used in all the data analyses and in comparison to the predicted data.

Table 2. Input soil properties of the top infiltration layer at each site

Site	Soil*	Texture Class	K_b† (mm/h)	Bulk Density (Mg/m^3)	Field Capacity (cm/cm)	Sand (%)	Clay (%)	Organic Matter (%)	CEC (cmol/kg)
Hollysprings	Providence	sil	0.47	1.34	0.240	2.0	19.8	0.81	9.3
Madison	Egan	sicl	1.56	1.21	0.450	7.0	32.2	3.70	25.1
Morris	Barnes	1	17.65	1.30	0.260	39.4	23.2	3.37	18.4
Presque Isle	Caribou	grsil	4.66	1.49	0.247	38.8	13.7	3.76	13.2
Watkinsville	Cecil	scl	19.75	1.59	0.210	66.5	19.6	0.89	4.8
Bethany	Shelby	sil	3.48	1.40	0.273	27.8	29.0	3.03	16.5
Geneva	Ontario	1	5.13	1.40	0.280	44.2	14.9	4.50	11.8
Guthrie	Stephensville	fsl	18.22	1.48	0.147	73.2	7.9	1.60	7.2

* Sil, silt loam; sicl, silty clay loam; 1, loam; grsil, gravel silt loam; scl, sandy clay loam; fsl, fine sandy loam.
† Obtained by optimizing equation 3 for fallow plots.

DATA ANALYSES

A program was written to optimize Green-Ampt K_e for selected storms under the WEPP daily simulation mode. The objective function was least square error (LSE) which was calculated by the square of the difference between measured and predicted runoff of the event. For each selected event/date, the objective function was minimized by iteratively varying K_e in the Green-Ampt equation, and the optimized K_e value was output when the LSE reached its minimum. This procedure was conducted in such a manner that the initial value of N_s prior to the rain event (estimated with eq. 2) remained unchanged and was used throughout the iterations. In most cases, the LSE was reduced to near zero for each event. However, due to a saturated condition in the top infiltration layer, the LSE could only be reduced to a constant level for a few events. In the latter case, the minimum K_e value which produced this constant LSE value was used as the optimized K_e value.

A K_e estimation equation was developed by relating the optimized K_e to the baseline conductivity (K_b), surface cover, and rainfall parameters. The equation was coded into the WEPP model, and runoff for each selected event was then predicted by running WEPP under the daily simulation mode. Goodness of fit between model predicted and measured runoff for individual events was evaluated using model efficiency defined by Nash and Sutcliffe (1970). The model efficiency, ME, is calculated by:

$$ME = 1 - \sum(Y_{obs} - Y_{pred})^2 / \sum(Y_{obs} - Y_{mean})^2 \quad (10)$$

where

Y_{obs} = measured storm runoff depth (mm)
Y_{pred} = model predicted storm runoff depth (mm)
Y_{mean} = mean measured storm runoff depth (mm)
ME = proportion of the initial variance of the observed values accounted for by the model, where initial variance is relative to the mean of all the observed values

ME can range from 1 to $-\infty$. If ME = 1, the model produces the exact prediction for each data point. A zero value of ME implies that a single mean measured value is as good an overall predictor as the model. A negative value of ME indicates that the measured mean is a better predictor than the model. The correlation analyses and linear and nonlinear best fit procedures in SAS were used to identify the major factors affecting K_e and to develop relationships between optimized K_e for individual storms and characteristics of the surface at the time of each storm.

Table 3. Effect of fall height on rain drop impact energy

Fall Height, h (mm)	Fall Velocity* (m/s)	Energy Ratio† (J/J)	Correction Factor (C_h)
0.5	2.96	0.160	0.840
1.0	3.98	0.289	0.711
2.0	5.19	0.491	0.509
3.0	5.89	0.632	0.368
4.0	6.34	0.732	0.268
6.0	6.92	0.872	0.128
20.0	7.41	1	0

* From J. O. Laws, (1941). Velocity measured for median drop size of 2.5 mm.
† Ratio of kinetic energy at each height to that at 20 m.

RESULTS AND DISCUSSION

EQUATION DEVELOPMENT

Adjustment of Canopy Cover for the Height Effect. Since canopy height has a significant impact on surface runoff, we developed a correction factor for adjusting the effectiveness of surface cover relative to infiltration as affected by canopy height. The fall velocity for a rain drop size of 2.5 mm (Laws, 1941) was used to compute kinetic energy of rainfall for a range of fall heights (table 3). Assuming that the terminal velocity has been reached at the height of 20 m, the energy ratio of kinetic energy at each height to the maximum energy at 20 m was calculated. The correction factor was defined as one minus the energy ratio. A nonlinear regression between the correction factor (C_h) and fall height (h) or average canopy height in meters was conducted, yielding:

$$C_h = e^{-0.336 \times h} \quad (11)$$

The r^2 is 0.99 (calculated by dividing the sum square error of regression by the sum square error of uncorrected total). This equation assumes: 1) median drop size of 2.5 mm; 2) no change of rainfall mass above and under canopy; and 3) 100% canopy cover. Droplets formed on the canopy may be greater than 2.5 mm, which is assumed to be offset by stem flow (Wischmeier, 1975). With equation 11, the effective canopy cover (C_{ef}) can be defined as:

Table 4. Correlation coefficients of selected variables to optimized event hydraulic conductivities

Site	Canopy Cover (C)	Effective Canopy Cover (C_{ef})	Residue Cover (G)	Total Effective Surface Cover (SC_{ef})	Residue Mass on Ground	Buried Residue Mass	Total Root Mass	Days Since Last Tillage	Rainfall Amount (P)	Rainfall-cover Term* (PC)
Hollysprings	0.11	0.11	0.26	0.27	0.24	0.17	0.31	0.20	0.31	0.41
Madison	0.20	0.19	0.03†	0.17	0.07†	0.08†	0.17	–0.01†	0.28	0.32
Morris	0.04†	0.05†	–0.02†	0.05†	–0.01†	–0.04†	0.04†	–0.15	0.68	0.20
Presque Isle	–0.04†	–0.04†	–0.16†	–0.08†	0.00†	0.04†	0.01†	–0.05†	0.33	0.06
Watkinsville	0.18	0.19	0.20	0.31	0.18	0.28	0.31	0.05†	0.40	0.49
Bethany	0.16	0.17	–0.10†	0.14	–0.09†	0.12†	0.06†	0.00†	0.27	0.22
Geneva	0.43	0.42	0.27	0.49	0.28	0.37	0.49	0.08†	0.64	0.82
Guthrie	0.14	0.15	0.06†	0.16	0.05†	0.30	0.27	–0.18	0.42	0.28
Pooled‡	0.10	0.12	0.13	0.20	0.14	0.17	0.06	0.11	0.38	0.39

* $PC = P \times SC_{ef}$.
† Not significant at the $\alpha = 0.05$ level.
‡ Using the lumped database from all the sites.

$$C_{ef} = C \times C_h \qquad (12)$$

in which C is the canopy cover. Furthermore, the total effective surface cover (SC_{ef}) can be computed by:

$$SC_{ef} = C_{ef} + G\,(1 - C_{ef}) \qquad (13)$$

where G is the residue cover. This equation assumes that the residue cover and the effective canopy cover are randomly distributed over the surface area.

Analyses of Variables Affecting K_e. Correlation coefficients of selected variables to optimized K_e values for all sites, along with the results from the pooled data, are given in table 4. Exponential, power, and logarithmic transforms of all the variables were tested, but did not significantly improve the correlation. Among the variables related to surface cover, canopy cover (C) was positively correlated to K_e for all sites except for Presque Isle where soil contained 32% rock by volume. Nonimbedded rocks are known to be effective in protecting the soil surfaces from soil crusting and therefore can improve K_e substantially. This time invariant rock cover might have reduced the effectiveness of canopy cover. Effective canopy cover (C_{ef}), corrected by canopy height, had greater correlation coefficients than canopy cover at five of the eight sites. The improvement was more evident for the test with the pooled data. This indicates that the adjustment of canopy cover by its height is useful. For residue cover (G), negative correlations which were not statistically significant were obtained at three sites. This could be due to the fact that most of the surface residue was either removed at harvest on Bethany and Presque Isle plots or buried with a fall turn-plow after harvest at Morris. Generally, over a growing season, K_e would be mainly dependent on canopy cover rather than residue cover since little residue is left on ground after seedbed preparation. Therefore, K_e may exhibit an increasing trend as canopy cover establishes. On the other hand, residue cover decreases with time due to decomposition. Thus, when most of the surface residue is removed at harvest, a negative correlation between K_e and G may be exhibited. A similar correlation was shown for variable of "residue biomass on ground" which is closely related to residue cover. As expected, the total effective surface cover (SC_{ef}) calculated by equation 13 provided a better overall correlation than using canopy or residue cover alone. This suggests that SC_{ef} is a better predictor for the effect of surface cover on K_e.

Buried residue mass and total root mass (live plus dead) were both positively related to K_e at most sites (table 4). Total root mass showed a similar or a better correlation than buried residue mass on all sites. But for the pooled data, buried residue mass exhibited a much stronger relationship with K_e than did total root mass. However, the incorporation of these two variables into the equation with the presence of SC_{ef} improved model predictability only slightly due to their interrelations. For simplicity, they were not included. As to the variable of "day since last tillage", it did not exhibit a consistent relationship to K_e (table 4). The correlation was not significant at six of the eight sites, indicating that it is not a good predictor for K_e prediction under the conventional tillage systems used in this study.

Table 5. Regression coefficient 'c' for the model of $K_e - K_{bare}(1 - SC_{ef}) = c \times PC$*

Site	Coefficient c	r^2
Hollysprings	0.0698	0.305
Madison	0.0943	0.413
Morris	0.2341	0.261
Presque Isle	0.0617	0.139
Watkinsville	0.2823	0.460
Bethany	0.0899	0.178
Geneva	0.5050	0.766
Guthrie	0.2248	0.216

* All regressions are significant at 0.0001 level.

The rainfall amount (P) showed the strongest correlation with K_e at all sites among all the variables except for cross-product (PC). Rainfall alone explained 7 to 40% of the total variation of the optimized K_e for the sites studied. The effects of rainfall characteristics on K_e or infiltration rate were reported in several studies (Wischmeier, 1966; Rawls et al., 1991). Rawls et al. (1991) found that the steady state infiltration rate at harvest with 90% canopy cover increased 132% for the corn and 56% for the soybean as the intensity increased from 76 to 127 mm/h. This behavior could be explained by macropore-flow phenomena. As the rainfall amount or intensity increases, water supply for infiltration increases so that more macropores would be contributing to water transport. Another possible explanation might be the

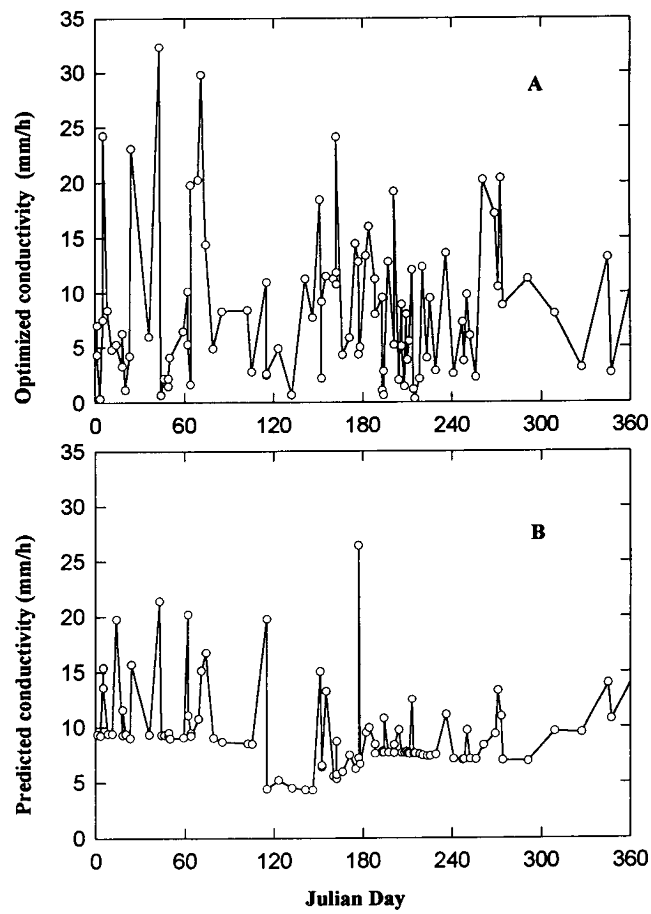

Figure 1–Seasonal variation of optimized and predicted event effective hydraulic conductivities for conventional corn at the Watkinsville site.

Table 6. Total rainfall, optimized and predicted mean effective conductivities (K_e), and measured and predicted total runoff volumes for the selected events

Site	Management	Total Rainfall	K_e* (mm/h) Optimized	K_e* (mm/h) Predicted	Total Runoff (mm) Measured	Total Runoff (mm) Predicted	Model Efficiency† (ME)
Holly-springs	fallow	5742	0.53				
	corn	5049	1.34	1.20	1793	2014	0.582
Madison	fallow	1553	1.54				
	corn TP	1310	1.83	1.62	322	311	0.783
	corn No TP	1359	1.76	1.75	311	275	0.747
	oats	410	1.86	1.76	86	88	0.775
Morris	fallow	1985	5.85				
	corn	1987	6.11	6.74	319	310	0.340
Presque Isle	fallow	1321	1.53				
	potato	1296	1.57	2.75	432	231	0.291
Watkins-ville	fallow	4277	3.34				
	corn	3566	8.45	9.66	675	793	0.823
	cotton	3846	7.36	8.65	834	911	0.791
Bethany	fallow	3330	1.42				
	corn	3375	1.73	1.60	1375	1308	0.845
Geneva	fallow	2292	2.40				
	winter rye	1912	3.95	2.91	375	534	0.511
	soybean	1446	8.70	3.66	51	338	xx
Guthrie	fallow	5313	5.58				
	cotton	4820	8.16	8.87	1239	1204	0.793

* Means of all selected events.
† Calculated on an event basis; xx indicates a negative ME.

spatial variation of K_e. For large storms, sufficient water supply tends to maintain more area under ponded conditions which ensure a relatively high conductivity in the area. As a result, the averaged K_e value would be much higher for the larger storms.

The interactions among the independent variables were also examined. A strong interaction existed between rainfall amount and total effective surface cover. The PC of these two variables exhibited a better overall correlation coefficiency than either SC_{ef} or P (table 4). On all sites, PC provided a much stronger relationship to K_e than SC_{ef}. The correlation was improved on four of the eight sites using PC instead of P. The lower correlation on the four sites might have been caused by the removal or burying of surface residue at or immediately after harvest. However, an analysis of pooled data from all the sites showed a higher correlation coefficient for PC than for either P or SC_{ef} alone. This indicates that PC is a better predictor for use in adjusting K_e and is probably a better variable to represent the different cropped conditions. It is known that a high macroporosity produced under agricultural management practices is often associated with a high plant and/or residue biomass. A high surface cover is often accompanied by a high macroporosity which directly determines the effect of rainfall on K_e. This situation could be represented if the PC variable is used. Thus, only the PC variable was selected and used in the final model formulation.

Adjustment of K_e for Different Surface Conditions. The effective hydraulic conductivity for any given area and surface conditions could be conceptualized as the weighted average of the K_e in the bared area (K_{bare}) and the K_e in the covered area. The K_{bare} could be estimated by equation 3. The K_e in the covered area was closely related to PC and could be well represented with this variable. Thus, a mathematical expression can be written as:

$$K_e = K_{bare}(1 - SC_{ef}) + c \times (PC) \quad (14)$$

where c is a coefficient. This model formulation attempts to reflect the general trends. For the bare case, equation 14 reduces to $K_e = K_{bare}$ as PC vanishes. The effective hydraulic conductivity is adjusted only for tillage/crust effect. Under the fully covered conditions, it is adjusted for the effects of surface cover and rainfall amount. As mentioned earlier, the transformation of PC did not improve its correlation to K_e. The linear relation between K_e and PC was therefore employed. Equation 14 can be rearranged as:

$$K_e - K_{bare}(1 - SC_{ef}) = c \times PC \quad (15)$$

in which PC is the only independent variable, and the terms on the left side can be treated as a dependent variable. Thus a linear regression with zero intercept for equation 15 can be conducted on data from each site to estimate 'c'. The results are given in table 5. All the regressions were significant at 0.0001 level. Further studies found that c was strongly related to basic soil properties such as sand and clay contents, or with baseline hydraulic conductivity (K_b, table 2) that can be estimated from basic soil properties (Risse et al., 1995). The linear relationship can be described by:

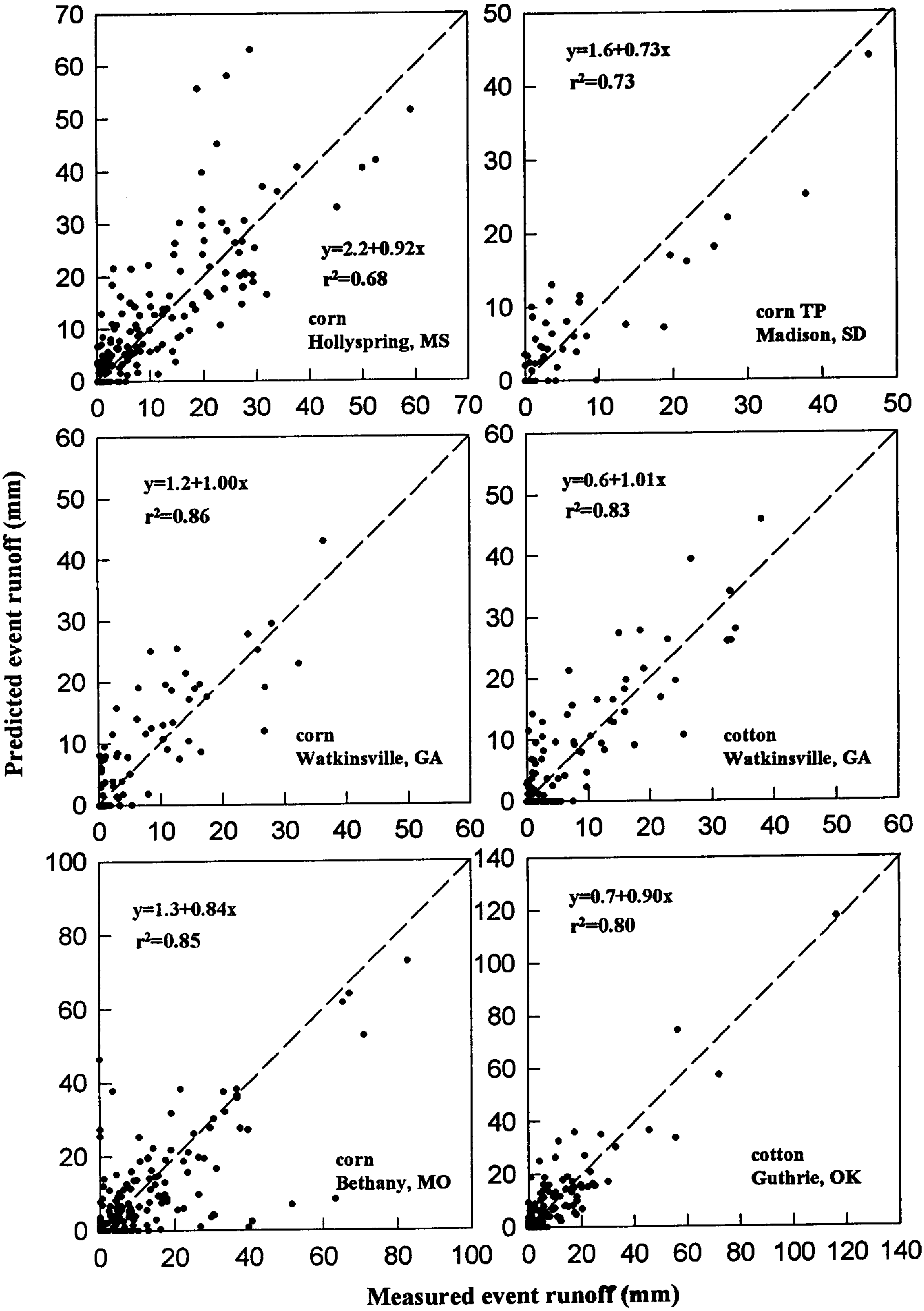

Figure 2–Plots of model predicted vs. measured storm runoff for the selected sites and cropping systems. Dash line is 1:1 line.

$$c = 0.0534 + 0.01179 \times K_b \quad (16)$$

where K_b is in mm/h. The r^2 of regression is approximately 0.95. It should be pointed out that c on the Geneva site was not used in the regression because it was several times higher than those from the soils with similar soil properties. With the relationships developed above, the final adjustment equation can be written as:

$$K_e = K_{bare}(1 - SC_{ef}) + (0.0534 + 0.01179 \times K_b) \times P \times SC_{ef} \quad (17)$$

Conceptually, this equation is composed of two additive components: K_{bare} for the bare area and effective hydraulic conductivity in the covered area. Hydraulic conductivity for any unit area is the summation of the two components.

Equations 8 and 9 were proposed for use with a single storm: we tested those relationships with our data to check their applicability. The results indicated that they did not provide a good K_e prediction for multiple rains or over a long term. This may be due to the fact that the decay function does not apply to cropped conditions. It is known that macropores are often developed under certain cropped conditions such as conservation tillage, and they can increase hydraulic conductivity significantly. Thus under these conditions, an exponential function is not suitable to describe the temporal variation of K_e since last tillage. As is shown in figure 1a where optimized K_e values for the selected storms are plotted over time for continuous corn at the Watkinsville site, the optimized K_e did not decrease temporally since spring tillage. Interestingly, the relatively low rather than high K_e values occurred during the seedbed preparation period (from Julian Day 90 to 150). Another limitation of using a decay function for K_e prediction is that it does not allow prediction of values which are higher than K_b. This is not always the case for the cropped conditions; under certain circumstances, K_e can be higher than K_b due to the effect of macroporosity.

Performance of the New Equation

Equation 17 was then used in WEPP to predict K_e and runoff under the continuous simulation mode of WEPP. Although there existed a large variability of optimized K_e (fig. 1a), the average K_e value could be used to indicate model performance in representing the different surface conditions or management practices. The mean value of optimized K_e was consistently higher under row-cropped conditions than that on the continuous companion fallow plots. This trend was well represented by the predicted K_e values (table 6).

For runoff predictions, regression showed that the total measured runoff and the total predicted runoff of the selected events matched well ($r^2 = 0.94$) with little bias (slope = 1.01). Results for individual storm prediction are summarized in table 6. The average model efficiency was 0.66 without soybean data from the Geneva site, which was predicted rather poorly. The relatively high ME values suggest that the adjustment equation predicts runoff reasonably well for each individual storm. This is also shown in figure 2, where the predicted and measured runoff volumes of each individual storm on selected data are plotted and linear regression results are presented.

Temporal changes of K_e and storm runoff were examined. Temporal variation of K_e is shown in figure 1 for the Watkinsville site with continuous conventional corn. The large variability of K_e between the adjacent events might have been due to the yearly differences in crop management such as tillage practices because these events were selected from seven different years. It might have also been attributed to the effect of storm size. On this site, the corn residue was shredded and left on ground at harvest and turn plowed around the end of March of the next year. The corn was usually planted in late April or early May (near Julian Day 120). Thus, the soil surfaces were exposed or not well protected from April to June until a canopy was established. This explains the reason why relatively small values of both optimized and predicted K_e occurred during the unprotected period. The similarity in trend suggests that the seasonal variation of K_e due to crop management is represented by the prediction equations. The changes of measured and predicted event runoff with time are shown in figure 3. The measured runoff in figure 3a and the predicted runoff in figure 3b agreed well. Most of runoff was produced during the summer season. This is likely due to several reasons. First of all, most heavy storms occurred during the summer season, and the high intensity rains tended to produce more runoff. Secondly, the bare soil surfaces, before canopy was fully established, were subjected to rain drop impact and to formation of surface seals which increased runoff considerably. Finally, even under full canopy cover, the canopy cover was not as effective as shredded corn stalk mulch in preventing surface runoff.

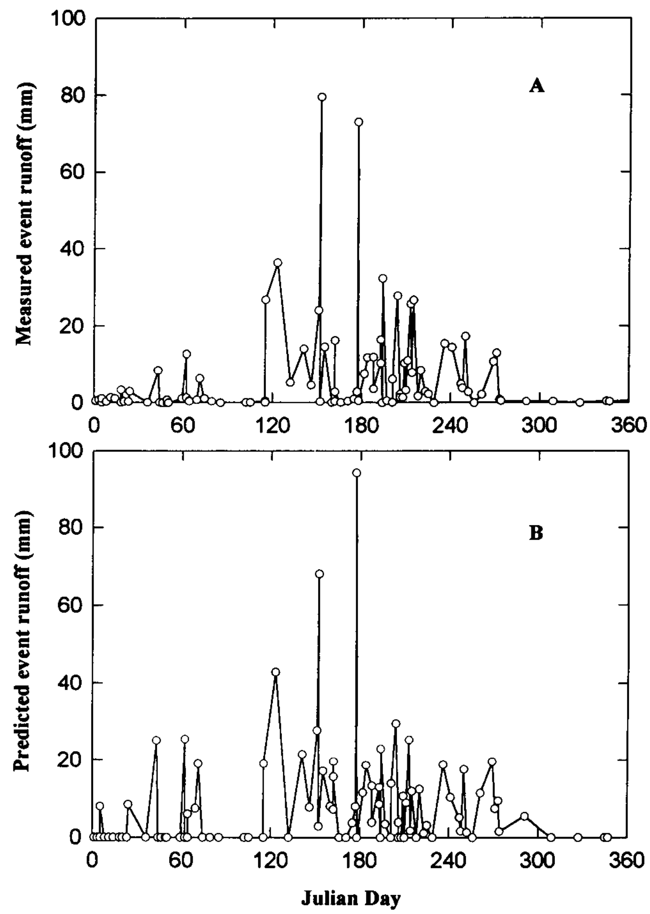

Figure 3–Seasonal distribution of measured and predicted event runoff for conventional corn at the Watkinsville site.

Conclusions

Canopy height has a significant effect on K_e. Based on raindrop impact energy, a statistical equation was developed to quantify this relationship. Results showed that the correlation between optimized K_e and canopy cover was improved if the effect of canopy height on infiltration was accounted for.

Among surface cover related variables, C, C_{ef}, G, and SC_{ef} were positively related to K_e on most sites. Under certain circumstances, negative correlations which were not statistically significant occurred on some sites. However, an overall test using the pooled data revealed that SC_{ef} was the best variable to represent the effect of total surface cover on K_e. Buried residue mass and total root mass, which were correlated to surface biomass, were also positively correlated with K_e. Rainfall amount (P) exhibited a very strong correlation with K_e at all sites. But the product of P and SC_{ef} provided a better overall correlation than either P or SC_{ef} alone, indicating a positive interaction between P and SC_{ef}. Thus, only PC was used in the new equation.

An interactive term consisting of P, SC_{ef}, and K_b was developed to predict K_e for cropped conditions. The predicted runoff of each individual storm agreed reasonably well with the measured data. The average model efficiency was 0.66. The seasonal variations of K_e and runoff were also represented in the new equation. It should be pointed out that the equation is sensitive to the SC_{ef} factor. A good estimate of this variable is critical to obtaining satisfactory predictions.

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