WATER RESOURCES BULLETIN
VOL. 32, NO. 1 AMERICAN WATER RESOURCES ASSOCIATION FEBRUARY 1996

CURVE NUMBERS AND GREEN-AMPT EFFECTIVE HYDRAULIC CONDUCTIVITIES[1]

M. A. Nearing, B. Y. Liu, L. M. Risse, and X. Zhang[2]

ABSTRACT: The SCS curve number method is an accepted method for estimating surface water runoff caused by rainfall. Several modern process-based hydrologic models, including the Water Erosion Prediction Project (WEPP) model, use the Green-Ampt infiltration equation, but the basis for selecting model parameters is not as comprehensive as for curve number selection. The purpose of this study was to quantitatively relate curve numbers to Green-Ampt effective conductivity parameters, K_e, so that the information available relative to application of curve number technology may be applied to WEPP for predicting runoff from rainfall. Data used to develop relationships included descriptions of 43 soils, CLIGEN-generated weather information for ten geographic locations in the U.S., and eight different types of cropping practices. Values of K_e were derived by optimizing WEPP model output to match that predicted by curve numbers for a 20-year weather sequence. Relationships were developed to describe the optimized K_e values for both fallow and cropped conditions. The relationships were tested on approximately 350 plot years of measured data from 11 runoff and erosion stations in the U.S. and shown to perform as well as or better than the SCS curve number approach for individual storm predictions of runoff volumes.
(KEY TERMS: erosion; infiltration and soil moisture; modeling; runoff; surface water hydrology.)

INTRODUCTION

The curve number method for predicting surface runoff volume from rainfall is accepted technology. All of the soils in the U.S. are assigned to one of the four hydrologic soil groups, and curve numbers have been established for an extensive list of land uses. Curve numbers are used by the USDA-Soil Conservation Service for engineering design of hydraulic structures (USDA-SCS, 1985) and for evaluating urban hydrology for small watersheds (USDA-SCS, 1986). The curve number has also been used extensively in various hydrologic, erosion, and water quality models developed by the USDA-Agricultural Research Service, including CREAMS (Knisel, 1980), EPIC (Sharpley and Williams, 1990), SWRRB (Williams *et al.*, 1985; Arnold *et al.*, 1990), and AGNPS (Young *et al*, 1989). Curve numbers have been calibrated and evaluated for many sets of measured runoff data and are known to be generally reliable over a wide range of geographic, soil, and land management conditions. The curve number method generates estimates of runoff depth, Q (mm), as a function of rainfall depth, P (mm), and a storage term, S, which is a function of the curve number, N. Curve numbers are assigned based on soil type (hydrologic soil group) and land use, and are modified depending on soil moisture content at the time of the rainfall. Details of the curve number method are given in the USDA-SCS National Engineering Handbook, Section 4 (USDA-SCS, 1985).

The Green-Ampt equation is an approximate model for infiltration which is based on Darcy's law for water flow through soil. The original equation (Green and Ampt, 1911) was applicable for infiltration of ponded water through a homogeneous profile. The model assumes plug-flow of water through a soil, with a well-defined wetting front which moves downward with time and separates the wet soil from the drier soil underneath. Chu (1978) developed a method for applying the Green-Ampt equation to the case of infiltration during unsteady rainfall. The Green-Ampt equation (Green and Ampt, 1911) has been used extensively in hydrologic models. It is used in the CREAMS (Knisel, 1980) model, in the Storm Water Management Model (SWMM) (Huber and Dickinson, 1988), and in the USDA Water Erosion Prediction Project (WEPP) model (Laflen *et al.*, 1991a; Lane and Nearing, 1989).

[1]Paper No. 94119 of the *Water Resources Bulletin*. **Discussions are open until August 1, 1996.**
[2]Respectively, Research Engineer, Post-Doctoral Scientist, Research Engineer, and Post-Doctoral Scientist, USDA-Agricultural Research Service, National Soil Erosion Research Laboratory, 1196 SOIL Building, Purdue University, West Lafayette, Indiana 47907-1196.

The key parameters needed to use the Green-Ampt equation are the effective matric potential, N_s (m), and the Green-Ampt effective hydraulic conductivity parameter, K_e (m/s). Ns is a function of the water content of the soil, Θ, and the average capillary potential across the wetting front, Ψ_w. Brakensiek (1977) presented an equation whereby the average capillary potential across the wetting front is calculated from the water entry suction of the soil, h_{we}, and a parameter η, both of which he estimated using procedures given by Brooks and Corey (1964). This procedure for calculating Ψ_w was discussed in detail by Rawls and Brakensiek (1983). The Green-Ampt effective hydraulic conductivity parameter, K_e, is approximately equal to one-half the saturated hydraulic conductivity of the soil, K_s (Bouwer, 1969).

Rawls and Brakensiek (1982, 1983) and Rawls *et al.* (1993) discussed methods of estimating K_s as a function of soil properties. These studies have utilized data from either saturated hydraulic conductivity measured on soil cores in the laboratory or from field infiltrometer measurements. Rawls and Brakensiek (1986) performed a comparison between runoff predictions from Green-Ampt and those from curve numbers using runoff measurements from 330 storms from 17 small watersheds. They used the method of Rawls and Brakensiek (1983) to estimate effective conductivity values. Their results showed that the Green-Ampt approach predicted runoff volumes with less bias and slightly more accuracy than did the curve number approach. Rawls and Brakensiek (1986) did not attempt to document the quantitative relationships between effective hydraulic conductivity and curve numbers.

Risse *et al.* (1994) evaluated K_e using natural runoff plot data from seven sites in the U.S. as applied to the WEPP model. Rudra *et al.* (1985) performed a similar analysis by using data from a site in Ontario with the CREAMS model. Nonetheless, reliable values for K_e for a wide range of soil types under natural rainfall conditions are extremely limited, and the effects of land use on effective conductivity are even less well documented.

The purpose of this study was to investigate the relationships between curve numbers and effective conductivity values for the Green-Ampt equation. The WEPP continuous simulation model was used. The matric potential term was calculated using the method in WEPP, which was that proposed by Brakensiek (1977) and by Rawls and Brakensiek (1983). Initial water content of the soil was calculated by the WEPP continuous simulation model. Optimum K_e values were determined by adjusting the input values of K_e until average annual runoff volumes were equal for the curve number and WEPP methods for 20-year simulations. Equations were developed for optimum K_e as a function of soil properties for bare soil conditions and for K_e as a function of land use. The resultant relationships were tested on a storm-event basis by using measured data from natural runoff plot data from 11 sites in the U.S.

METHODS

Soils Data

Soils data for 43 soils were obtained from three sources (Table 1). Data for 30 soils were taken from the study of the WEPP cropland erodibility sites (Laflen *et al.,* 1991b; Elliot *et al.,* 1989). These sites were sampled and analyzed by the USDA-SCS Soil Survey Laboratory. Complete pedon descriptions (i.e., complete soil profile characterizations) were available for each of these 30 soils. Data for 11 additional soils were obtained from the repository of soil erosion data located at the National Soil Erosion Research Laboratory. These soils were located on natural runoff plot sites from 11 erosion research stations located in nine different states of the U.S. The data from the WEPP experimental sites and from the natural runoff plots contained only one soil of the hydrological soil group A. For this reason, data for two additional soils of hydrologic soil group A were taken from the SCS soils data base. The soils data were used to build soil input files for the WEPP model. The required soils data included rill and interrill erodibilities and albedo for the top 20 cm thick soil layer; for the lower soil layers, data included percent of sand, clay, organic matter, and rock fragments, plus the cation exchange capacity.

Saturated conductivities for the soil sublayers – i.e., soil below the top 20 cm – are calculated internally in the WEPP model by using equations developed for the EPIC model (Sharpley and Williams, 1990). Saturated conductivities of the soil sub-layers do not directly influence the K_e used in the Green-Ampt infiltration calculations but do influence percolation rates and thus estimated soil moisture through the simulation period. The wetting front capillary potential term, Ψ_s, is calculated in WEPP by using the method described by Rawls and Brakensiek (1983).

Climate Data

Two types of climate data were used in this study. The CLIGEN climate generator (Nicks *et al.,* 1993) was used to generate 20-year weather sequences for 10 representative geographic locations in the U.S.

TABLE 1. Characteristics for Soils Used in the Study. The Green and Ampt effective conductivity (K_e) values for each soil were derived from optimization to runoff from fallow soil curve numbers using the WEPP model and a 20-year CLIGEN generated weather file for Jefferson City, Missouri.

Soils	Sand (percent)	Clay (percent)	Hydrologic Soil Group	Simulator Measured Effective Conductivity (mm/h)	Optimized Effective Conductivity (mm/h)	Estimated Effective Conductivity (mm/h)
Amarillo*	85.0	7.3	b	15.00	7.03	7.29
Barnes**	39.4	23.2	b		4.10	4.01
Barnes*	48.6	17.0	b	19.10	4.69	4.67
Barnes*	39.3	26.5	b	16.70	4.40	4.00
Bonifay*	91.2	3.3	a	34.80	14.8	14.2
Caribou**	38.8	13.7	b		4.30	3.96
Cecil*	69.9	11.5	b	13.30	7.42	5.96
Cecil**	66.5	19.6	b		6.25	6.20
Collamer*	6.0	15.0	c	3.60	0.68	0.70
Colonie***	90.5	2.1	a		14.5	14.2
Egan**	7.0	32.2	b		1.66	1.67
Frederick*	25.1	16.6	b	2.90	2.69	2.98
Gaston*	37.2	37.9	c	3.60	1.76	1.73
Grenada*	1.8	20.2	c	3.40	0.64	0.56
Heiden*	8.6	53.1	d	4.70	0.31	0.34
Hersh*	72.3	10.9	b	15.80	6.45	6.38
Hiwassee*	63.7	14.7	b	13.60	6.25	5.78
Keith*	48.9	19.3	b	3.50	4.69	4.76
Lewisburg*	38.5	29.3	c	3.70	1.76	1.77
LosBanos*	15.5	43.7	c	3.90	0.83	1.01
Manor*	44.0	25.2	b	10.00	4.59	4.34
Mexico*	5.5	25.3	d	6.20	0.32	0.34
Miami*	4.2	23.1	b	0.86	1.56	1.47
Miamian*	31.3	25.9	c	4.40	1.37	1.53
Monona**	7.1	23.5	b		1.66	1.68
Nansene*	20.1	12.8	b	5.30	2.15	2.62
Ontario**	44.2	14.9	b		4.20	4.35
Opequon*	37.7	31.1	c	7.60	1.86	1.74
Palouse*	9.8	20.1	b	2.60	1.81	1.88
Pierre*	16.9	49.5	d	2.40	0.39	0.34
Portneuf*	19.5	11.1	b	7.90	2.00	2.48
Pratt***	89.0	2.2	a		13.3	14.2
Providence**	2.0	19.8	c		0.68	0.57
Sharpsburg*	5.2	40.1	b	7.30	1.61	1.75
Shelby**	27.8	29.0	b		2.93	3.17
Stephensville**	73.2	7.9	b		6.15	6.44
Sverdrup*	75.3	7.9	b	20.30	6.25	6.59
Thatuna**	28.0	23.0	c		1.27	1.42
Tifton*	86.4	2.8	b	14.90	6.64	7.39
Tifton**	87.0	5.7	b		7.23	7.43
Williams*	40.8	26.9	b	8.30	4.40	4.11
Woodward*	51.7	13.0	b	12.00	4.49	4.89
Zahl*	46.3	24.0	b	5.70	4.98	4.50

*Data from WEPP cropland erodibility study of Elliot *et al.* (1989).
**Data from USLE plot information and SCS soils data base (Risse, 1994).
***Data from SCS Soil Survey Investigations (SCS, 1967).

These sequences were used for purposes of optimization of K_e values. For purposes of testing the derived estimation equations for K_e against measured runoff data, recorded rainfall data from the measured data for the runoff plots were used. Summary data was available for all of the locations except for Pendleton, Oregon, for which the necessary information was obtained directly from the rainfall charts from the sites.

Management and Topographic Data

Management files for WEPP were constructed to represent various management practices for the study. The WEPP-K_e was optimized against curve number for fallow, fall-tilled corn, fall-tilled soybeans, conservation-tilled corn, conservation-tilled soybeans, winter wheat, alfalfa, pasture, and meadow management practices. Representative curve number values (Table 2) were chosen from the National Engineering Handbook, Section 4 (USDA-SCS, 1985). For measured data, WEPP management files were constructed to represent as closely as possible the actual management which was applied to each plot, including tillage types, tillage dates, planting dates, harvest dates, and crop yields.

TABLE 2. Curve Number Values for Each of the Management Practices and Soil Hydrologic Groups Used in the Study.

Management Practice	Hydrological Soil Group A	B	C	D
Fallow	77	86	91	94
Conventional Corn	72	81	88	91
Conventional Beans	72	81	88	91
Conservation Corn	71	80	87	90
Conservation Beans	71	80	87	90
Wheat	65	76	84	88
Alfalfa	58	72	81	85
Pasture	49	69	79	84
Meadow	30	58	71	78

Source: U.S. Dept. Agric., Soil Conservation Service, 1985, National Engineering Handbook, Section 4: Hydrology, U.S. Government Printing Office, Washington, D.C.

Analyses and Optimization Procedure

Runoff estimated by the Green and Ampt equation is influenced by both the effective conductivity and Ψ_s. Preliminary sensitivity analysis of the Green and Ampt model in WEPP indicated that Ψ_s and K_e were interdependent in terms of infiltration volume predictions. This interdependence made it impossible to perform two parameter optimizations for the Green and Ampt model to simultaneously obtain optimum values for both parameters from a data set. Therefore, we chose to use a consistent method for estimation of soil water content and Ψ_s, and focused on calibrating to the effective conductivity value.

The WEPP model for this study used a constant value of K_e. The value of K_e was read from the soil input file and used directly in the Green-Ampt model with no internal modifications to account for temporal changes as a function of management or weather. The optimization procedure consisted of finding the value of K_e for which the average annual runoff for a 20-year weather sequence predicted by WEPP matched that predicted by curve number calculations. Curve numbers were adjusted for antecedent moisture conditions based on the previous five day rainfall, as outlined in the USDA-SCS National Engineering Handbook, Section 4 (USDA-SCS, 1985).

Two soils from each of the four hydrologic soil groups were chosen to evaluate the effect of climate on the optimized K_e value. K_e was obtained for each of the eight soils at each of the 10 geographic locations in the U.S.

The optimized K_e values for the 43 soils for fallow conditions were tabulated and statistically analyzed. Estimation equations were developed for relating these optimized K_e values to soil properties. In the following discussion, values referred to as "estimated" are those which are calculated from relationships which were derived between the optimized values and soil characteristics. Values referred to as "optimized" were those that were determined from the curve number optimization procedure discussed above. Fifteen soils were used to establish relationships between K_e and curve number for cropped conditions: three from hydrologic soil group A, six from hydrologic soil group B, three from hydrologic soil group C, and three from hydrologic soil group D. These soils were chosen to represent a cross section of the soils in each hydrologic group based on the results from the analysis of fallow conditions. In what follows, effective hydraulic conductivity for fallow conditions will be referred to as K_{ef} so as to distinguish from K_e for cropped conditions.

Natural Runoff Plot Data

Natural runoff plot data were used from 11 locations in the U.S. to test the estimation relationships derived from the optimization of the Green-Ampt effective conductivity parameter to curve numbers. All of the 11 sites considered had data for fallow conditions. Data for five of the sites were for cropped conditions with conventionally-tilled corn, no-till corn, cotton, alfalfa, and bluegrass. Input files for soil, management, climate, and topographic data were constructed to represent the conditions for each individual runoff plot. Averages of the runoff data for replicated plots were used in all comparisons of measured versus predicted data points. Events were selected from the records for analysis based on the quality of the data. Runoff events were excluded if the data was incomplete or if there were obvious errors in the data, such as when measured runoff exceeded recorded precipitation amounts. Data were also excluded for cases where multiple days of rainfall were lumped into single data recordings.

The fit between model results and measured runoff for individual storm events was quantified in terms of model efficiency (Nash and Sutcliff, 1970). The coefficient of efficiency, E, is computed as:

$$E = 1 - \left[\sum \left(Y_{obs} - Y_{pred} \right)^2 / \sum \left(Y_{obs} - Y_{mean} \right)^2 \right] \quad (1)$$

where Y_{obs} is the observed storm runoff volume, Y_{pred} is the model calculated storm runoff volume, and Y_{mean} is the mean observed storm runoff volume.

The coefficient of model efficiency is the proportion of the initial variance in the observed values which is explained by the model, where initial variance is relative to the mean value of all the observations. Thus, E may range from 1 to $-\infty$. If E = 1, the model is predicting exactly the measured runoff volumes for every storm. A value of E = 0 would indicate that the sum of squares of the difference between the measured and the predicted is equal to the sum of squares difference between the observed values and the mean of the observed values. This indicates that the mean value of storm water runoffs from the data set would be as good a predictor of storm runoff as is the model. Negative values of E indicate that the observed mean is a better predictor of Y_{obs} than is the model.

We also use the model efficiency concept to quantify the difference between optimized and estimated values of effective conductivities. In this case, the Y_{obs} values are the optimized conductivities and the Y_{pred} values are the estimated conductivities.

RESULTS AND DISCUSSION

Fallow Conditions

Climate. Differences in climate between the ten geographic locations had relatively small effect on the optimized K_e values (Table 3) under fallow conditions. The coefficient of variation for the eight soils averaged 12 percent. Differences in K_e between locations were not consistent, but some trends were evident. Jefferson City, Missouri; Holly Springs, Mississippi; and Brunswick, Georgia, had somewhat higher than average K_e values for every soil type. These locations also had higher average annual rainfall than the other locations, with the exception of Tillamook, Oregon, which has the greatest annual rainfall among the selected sites. Heppner, Oregon, had consistently low values of K_e, and it also had low annual rainfall. Tucson, Arizona, however, with low annual rainfall, had K_e values near the middle of the range for all of the soils. In general, climate had a relatively minor influence on the optimization of K_e. The Jefferson City, Missouri, climate file was used for all further parts of this study because it was considered to be representative of the major rain-fed crop producing areas of the U.S. The results of the remainder of the study may be adjusted, if desired, for other locations in the U.S. based on the results presented in Table 3.

Relationship Between K_e and Curve Number: Results of the optimization relative to curve numbers for fallow conditions are presented in Table 1. There was a relatively wide range in values of effective conductivity for fallow conditions, K_{ef}, within the hydrologic soil groups B and C. Most of the variance of K_{ef}

TABLE 3. Optimized Green and Ampt Effective Conductivity Values for Fallow Conditions, K_{ef}, for Eight Soils at Each of Ten Geographic Locations With Generated Climate Data.

	A Group Soil		B Group Soil		C Group Soil		D Group Soil	
Location	Bonifay (mm/h)	Pratt (mm/h)	Tifton (mm/h)	William (mm/h)	Lewisburg (mm/h)	Miamian (mm/h)	Pierre (mm/h)	Mexico (mm/h)
Borger, Texas	14.26	12.70	6.45	4.20	1.71	1.37	0.37	0.29
Brunswick, Georgia	15.04	13.67	6.84	4.69	1.86	1.47	0.42	0.34
Heppner, Oregon	12.11	10.74	5.37	3.42	1.37	1.07	0.29	0.24
Holly, Mississippi	14.26	12.89	6.45	4.40	1.76	1.42	0.42	0.33
Jefferson City, Missouri	14.84	13.28	6.64	4.40	1.76	1.37	0.39	0.32
Morris, Minnesota	14.26	12.70	6.24	4.20	1.66	1.32	0.37	0.29
Portland, Oregon	10.94	9.77	4.98	3.13	1.22	0.98	0.23	0.23
Presque Isle, Maine	11.02	10.55	5.57	3.71	1.56	1.22	0.37	0.29
Tilamook, Oregon	12.89	11.52	5.86	3.91	1.51	1.22	0.35	0.29
Tucson, Arizona	14.65	13.18	6.15	4.00	1.61	1.27	0.37	0.29
$\bar{X}$	13.51	12.10	6.06	4.01	1.60	1.27	0.36	0.29
Sd	1.37	1.28	0.57	0.45	0.18	0.15	0.06	0.03

within those hydrologic soil groups could be explained in terms of the amount of sand in the soil (Figure 1). The size sampling for hydrologic soil groups A and D was relatively small compared to the other two groups, which is consistent with their occurrence in nature. Variance of K_{ef} within those two groups was relatively small. Suggested relationships for curve number optimized K_{ef} for fallow conditions are presented in Table 4. The relationship between curve number optimized K_{ef} and K_{ef} estimated from the relationships in Table 4 is shown in Figure 2. The regression between the optimized and estimated K_e values shown in Figure 2 gives an r^2 value of 0.99, a slope which is not statistically different from 1.0, and an intercept of zero. Thus, the relationships shown in Table 4 explain most (99 percent) of the variance in the optimized K_{ef} values with very little bias.

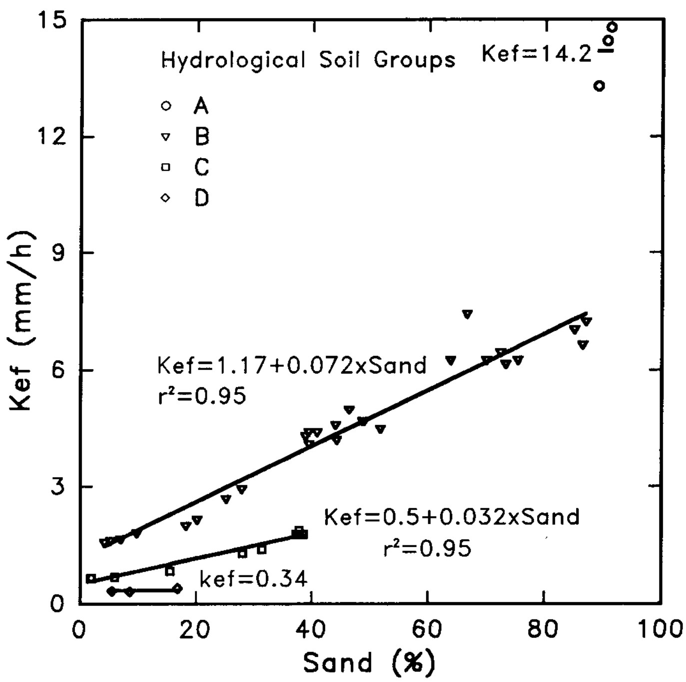

Figure 1. Optimized Effective Hydraulic Conductivity Values for Fallow Soil Conditions, K_{ef}, Versus Sand Content of the Soil.

TABLE 4. Relationships for Calculating Curve Number Optimized Green and Ampt Effective Conductivity Values for Fallow Condition, K_{ef}.

Hydrologic Soil Group	Formula	R2
A	$K_{ef} = 14.18$	
B	$K_{ef} = 1.17 + 0.072 \times sand$	0.95
C	$K_{ef} = 0.50 + 0.032 \times sand$	0.95
D	$K_{ef} = 0.34$	

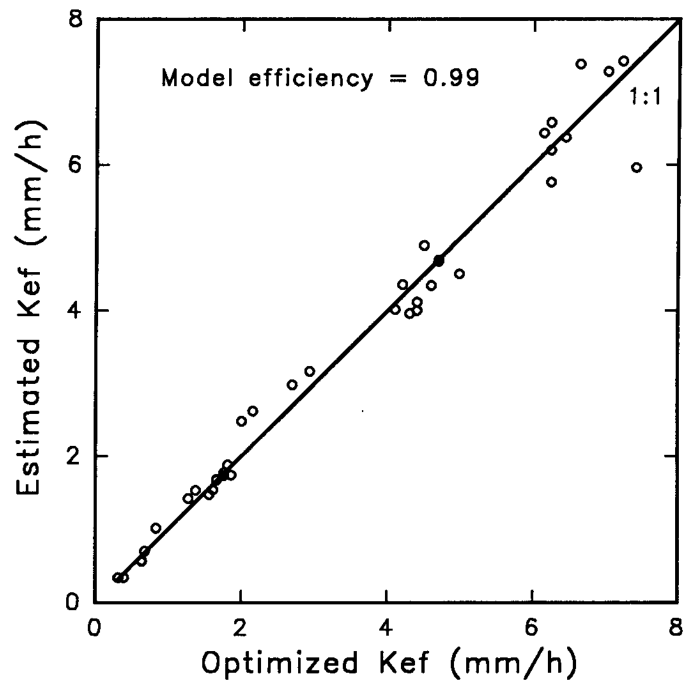

Figure 2. Estimated Values of Effective Hydraulic Conductivity Values for Fallow Soil Conditions, K_{ef}, From Relationships Presented in Table 4 Versus Curve Number Optimized K_{ef}.

Application to Measured Data. The runoff data used to test the K_{ef} relationships for fallow conditions are summarized in Table 5. The fallow plots had an average of 10 years of plot data per plot, and an average of two replications per site, for a total of greater than 200 plot-years of data. The number of events per site used in the analysis ranged from 60 at Madison, South Dakota, to 208 at Holly Springs, Mississippi. A total of 1162 storm events were used for the fallow condition, of which 786 were replicated. Curve numbers from Table 2 and the WEPP model with K_{ef} estimated from relationships in Table 4 were used to predict individual storm runoff amounts. Table 6 shows the results of the analysis. The Green-Ampt equation in WEPP predicted the average event runoff as well as did the curve number method. Model efficiency (Nash and Sutcliff, 1970) (see Equation 1) was better for the Green-Ampt model than for the curve number approach for every site except Pendleton, Oregon. Both methods had negative efficiency (and thus a poor fit) for Pendleton on an individual storm basis. For Bethany, Missouri, and Geneva, New York, the efficiencies were nearly the same. Measured vs. WEPP-predicted runoff for individual storm events are plotted for Watkinsville, Georgia; Guthrie, Oklahoma; Morris, Minnesota; and Holly Springs, Mississippi, in Figs. 3a, 3b, 3c, and 3d.

TABLE 5. Summary of Natural Runoff Plot Data Used to Evaluate the Curve Number and Green and Ampt Estimations of Runoff Values for Fallow Conditions.

Location	Soil	Years	Percent Slope	Number of Replicates	Number of Events
Bethany, Missouri	Shelby SiL	1931-1940	8.0	1	109
Castana, Iowa	Monona SiL	1960-1971	14.0	2	90
Geneva, New York	Ontario L	1937-1946	8.0	1	97
Guthrie, Oklahoma	Stephensville, FSL	1942-1956	7.7	1	170
Holly Springs, Mississippi	Providence SiL	1961-1968	5.0	2	208
Madison, South Dakota	Egan SiCL	1961-1970	5.8	2	60
Morris, Minnesota	Barnes L	1961-1971	5.9	3	72
Pendleton, Oregon	Thatuna SiL	1979-1989	16.0	2	82
Presque Isle, Maine	Caribou GrSiL	1961-1969	8.0	3	99
Tifton, Georgia	Tifton SL	1959-1966	3.0	2	65
Watkinsville, Georgia	Cecil SCL	1961-1966	7.0	2	110

TABLE 6. Measured Runoff Volumes, Curve Number, and WEPP-Predicted Runoff Volumes, and Model Efficiency for the Fallow Runoff Plot Data.

Site	Average Runoff Per Event			Model Efficiency	
	Measured (mm)	CN (mm)	WEPP (mm)	CN	WEPP
Bethany, Missouri	14.43	9.97	8.71	0.72	0.69
Castana, Iowa	11.47	11.87	12.15	0.10	0.37
Geneva, New York	7.87	6.00	4.66	0.58	0.57
Guthrie, Oklahoma	10.91	10.51	10.21	0.77	0.86
Holly Springs, Mississippi	15.17	12.64	13.46	0.78	0.86
Madison, South Dakota	7.96	6.67	6.27	0.69	0.73
Morris, Minnesota	5.55	8.71	8.47	–1.06	–0.49
Pendleton, Oregon	3.18	1.79	0.35	–0.33	–0.71
Presque Isle, Maine	6.91	4.81	3.21	–0.25	0.13
Tifton, Georgia	19.05	21.07	17.56	0.24	0.43
Watkinsville, Georgia	13.41	11.89	10.85	0.74	0.82

Cropped Conditions

Relationship Between K_e and Curve Number: Optimized K_e values for cropped conditions were relatively consistent when they were expressed as a ratio of K_e for the cropped condition to effective conductivity for the fallow condition, K_{ef}. This ratio did not vary greatly across hydrologic soil groups (Table 7). Hydrologic soil groups B and C did not show statistical difference in the K_e-cropped to K_e-fallow ratio, but the ratio for hydrologic soil group D was significantly greater, and the ratio for hydrologic soil group A was significantly lesser than that for soil groups B and C (except for the case of pasture). Table 8 presents recommendations for estimating K_e for cropped conditions from K_{ef} for fallow conditions. Figure 4 shows the relationship between K_e estimated using Table 8, and the optimized K_e from curve number.

Non-linear regression analysis was used to relate K_e for the cropped conditions to curve number by the equation

$$K_e = \frac{56.82 K_{ef}^{0.286}}{1 + 0.051 \exp(0.062 N)} - 2 \tag{2}$$

where K_{ef} is the effective conductivity for fallow conditions computed from relationships in Table 4 and N is curve number for the given soil hydrologic group and cropping condition. Figure 5 shows a plot of K_e optimized from curve number and K_e estimated using Equation (2) for the 15 soils and the eight different cropping practices used in the study. The overall fit between estimated and optimum K_e using Equation (2) is slightly better than that obtained using Table 8. However, the fit of the data for the smaller K_e values appears to be somewhat better using Table 8. Equation (2) is useful for estimating representative K_e values for management practices not shown in Table 8.

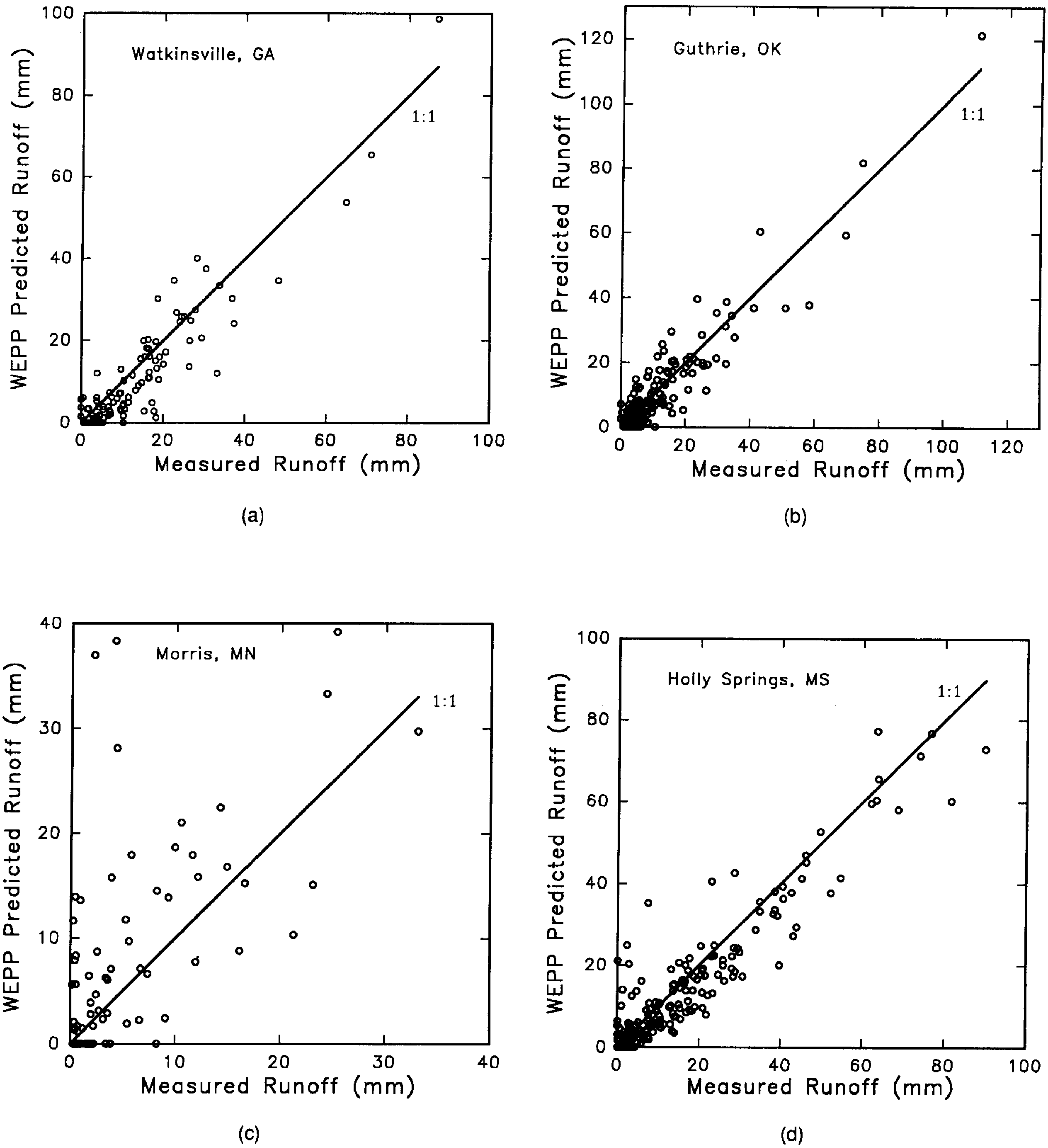

Figure 3. Measured Versus WEPP-Predicted Storm-by-Storm Runoff Volumes for Fallow Soil Conditions Using Effective Hydraulic Conductivity Values, K_{ef}, Estimated Using Relationships from Table 4 for Data from: (A) Watkinsville, Georgia; (B) Guthrie, Oklahoma; (C) Morris, Minnesota; and (D) Bethany, Missouri.

TABLE 7. Average Ratio of Effective Conductivity for Each Management Condition, K_e, to the Effective Conductivity for Fallow Soil Condition, K_{ef}.

Management	Hydrological Soil Group A	B	C	D
Fallow	1	1	1	1
Convention Corn	1.35 c	1.64 ab	1.47 bc	1.73 a
Convention Beans	1.39 c	1.72 b	1.64 b	2.00 a
Conservation Corn	1.48 c	1.81 b	1.74 b	2.21 a
Conservation Beans	1.50 c	1.89 b	1.94 b	2.49 a
Wheat	1.84 c	2.14 b	2.15 b	2.48 a
Alfalfa	2.86 b	3.74 b	3.79 b	6.23 a
Pasture	3.66 a	4.44 a	4.13 a	5.96 a
Meadow	6.33 b	8.66 b	9.75 b	15.45 a

*Mean values of K_e/K_{ef} followed by the same letter are not statistically different at p = 0.01 as determined by Duncan's multiple range tests for each management practice..

TABLE 8. Recommended Ratios of K_e-Cropped to K_e-Fallow to Use in Estimating K_e-Cropped from Table 4 Relationships.

Management	Hydrological Soil Group A	BC	C
Fallow	1.00	1.00	1.00
Convention Corn	1.35	1.58	1.73
Convention Beans	1.39	1.70	2.00
Conservation Corn	1.48	1.79	2.21
Conservation Beans	1.50	1.91	2.49
Wheat	1.84	2.14	2.48
Alfalfa	2.86	3.75	6.23
Pasture	3.66	4.34	5.96
Meadow	6.33	9.03	15.50

Application to Measured Data. The runoff data used to test the K_e relationships for cropped conditions is summarized in Table 9. The cropped plots had an average of 9.3 years of plot data on 17 plots from five locations, for a total of 158 plot-years of data. The number of events per plot used in the analysis ranged from 48 at Madison, South Dakota, to 163 at Holly Springs, Mississippi. A total of 980 storm events were used for the cropped condition, of which 470 were replicated. Curve numbers from Table 2 and the WEPP model with K_e estimated from Equation (2) were used to predict individual storm runoff amounts. Table 10 shows the results of this analysis. Overall, the Green-Ampt equation in WEPP and the curve number method predicted the average event runoff equally well.

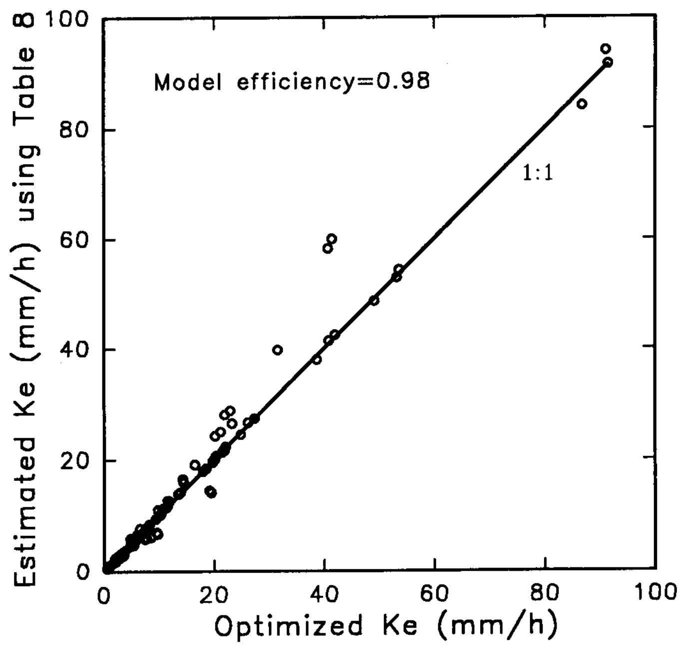

Figure 4. Effective Hydraulic Conductivity, K_e, for Cropped Conditions Estimated Using Ratios from Table 8 Versus Curve Number Optimized K_e Values.

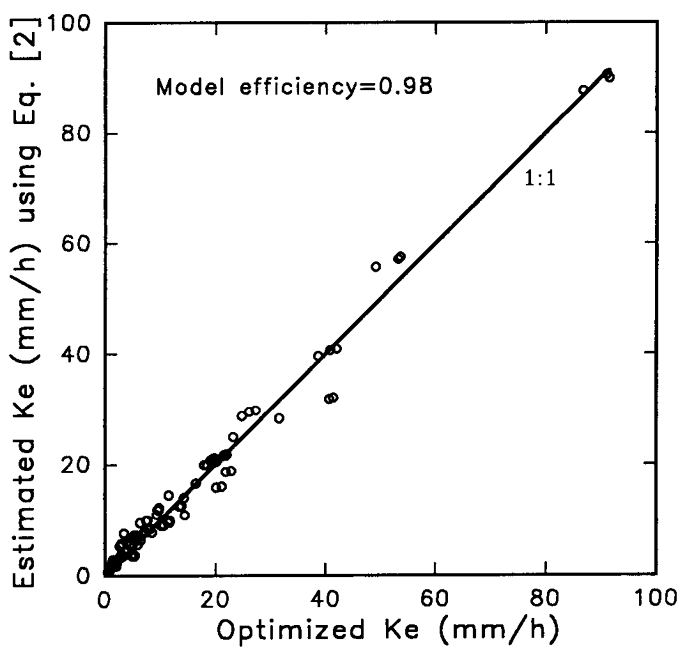

Figure 5. Effective Hydraulic Conductivity, K_e, for Cropped Conditions Estimated Using Equation (2) Versus Curve Number Optimized K_e Values.

TABLE 9. Summary of Natural Runoff Plot Data Used to Evaluate the Curve Number and Green and Ampt Estimations of Runoff Values for Cropped Conditions.

Location	Management Practice	Years	Number of Replicates	Number of Events
Bethany, Missouri	Alfalfa	1931-1940	1	83
Bethany, Missouri	Blue Grass	1931-1940	1	79
Bethany, Missouri	Corn	1931-1940	1	112
Guthrie, Oklahoma	Blue Grass	1942-1956	1	96
Guthrie, Oklahoma	Cotton	1942-1956	1	140
Holly Springs, Mississippi	Corn	1961-1968	2	163
Madison, South Dakota	Corn	1962-1970	3	48
Madison, South Dakota	No-Till Corn	1962-1970	3	50
Watkinsville, Georgia	Corn	1961-1967	2	97
Watkinsville, Georgia	Cotton	1961-1967	2	112

TABLE 10. Measured Runoff Volumes, Curve Number, and WEPP-Predicted Runoff Volumes, and Model Efficiency for the Cropped Runoff Plot Data. The estimates of effective conductivity are from the use of Equation (2).

Site	Management Practice	Average Runoff Per Event: Measured (mm)	Average Runoff Per Event: Curve Number (mm)	Average Runoff Per Event: WEPP (mm)	Model Efficiency: Curve Number	Model Efficiency: WEPP
Bethany, Missouri	Alfalfa	3.72	1.20	1.89	0.32	0.64
Bethany, Missouri	Blue Grass	3.88	1.26	0.84	0.43	0.33
Bethany, Missouri	Corn	12.3	6.66	4.42	0.66	0.47
Guthrie, Oklahoma	Blue Grass	1.96	1.97	2.36	0.58	0.85
Guthrie, Oklahoma	Cotton	8.85	8.97	8.80	0.68	0.80
Holly Springs, Mississippi	Corn	11.0	11.0	9.50	0.20	0.53
Madison, South Dakota	Corn	6.70	4.75	2.20	0.54	0.51
Madison, South Dakota	No-Till Corn	6.22	4.16	1.86	0.54	0.50
Watkinsville, Georgia	Corn	6.96	9.77	9.16	0.40	0.66
Watkinsville, Georgia	Cotton	7.44	7.98	8.73	0.50	0.73

Table 11 shows the results of using Table 8 ratio values for estimating K_e. These results were somewhat better overall than were the results using Equation (2). WEPP predicted the runoff better than did the curve number for eight of the ten data sets. Figure 6 shows the measured versus predicted runoff depths for individual storms on four of the cropped plots.

SUMMARY AND CONCLUSIONS

This study resulted in empirical relationships between the effective conductivity parameter in the Green-Ampt equation, K_e, and runoff curve numbers for both cropped and fallow conditions. The study also provided a means of estimating K_e as a function of soil hydrologic group, sand content, and management practice. Comparisons of predicted vs. measured runoff showed that the resultant relationships for estimating K_e worked as well as or better than the curve number approach. The K_e results presented in this study are intended to be used to represent average or representative conditions for specific soil, climatic, and land use conditions. The WEPP model currently has two options for applying the Green-Ampt equation: one where K_e varies temporally from a baseline value as a function of management influences, including such things as tillage, canopy and residue cover, and roots; and the other that uses a non-varying K_e that must be provided by the user to produce the desired annual runoff. The K_e values presented in this study are intended for use in the non-temporally varying Green-Ampt infiltration application.

TABLE 11. Measured Runoff Volumes, Curve Number, and WEPP-Predicted Runoff Volumes, and Model Efficiency for the Cropped Runoff Plot Data. The estimates of Effective Conductivity are from the use of Table 8.

Site	Management Practice	Average Runoff Per Event Measured (mm)	Average Runoff Per Event Curve Number (mm)	Average Runoff Per Event WEPP (mm)	Model Efficiency Curve Number	Model Efficiency WEPP
Bethany, Missouri	Alfalfa	3.72	1.20	1.87	0.32	0.63
Bethany, Missouri	Blue Grass	3.88	1.26	0.74	0.43	0.28
Bethany, Missouri	Corn	12.3	6.66	6.08	0.66	0.63
Guthrie, Oklahoma	Blue Grass	1.96	1.97	1.24	0.58	0.91
Guthrie, Oklahoma	Cotton	8.85	8.97	7.94	0.68	0.80
Holly Springs, Mississippi	Corn	11.0	11.0	12.8	0.20	0.39
Madison, South Dakota	Corn	6.70	4.75	4.76	0.54	0.76
Madison, South Dakota	No-Till Corn	6.22	4.16	3.97	0.54	0.72
Watkinsville, Georgia	Corn	6.96	9.77	8.14	0.40	0.74
Watkinsville, Georgia	Cotton	7.44	7.98	7.08	0.50	0.77

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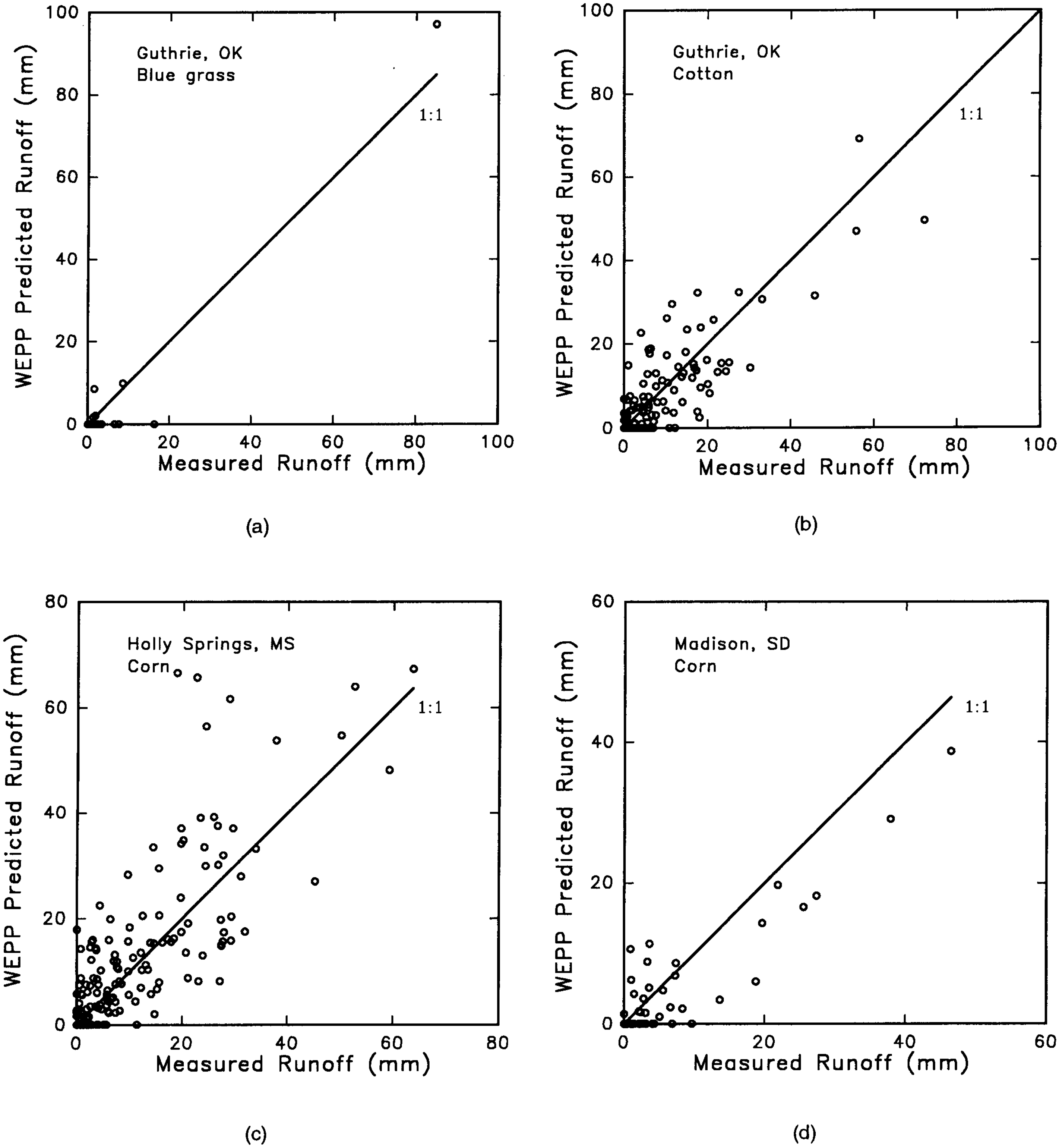

Figure 6. Measured Versus WEPP-Predicted Individual Storm Runoff Volume for Cropped Conditions Using Effective Hydraulic Conductivity Values, K_e, Estimated Using Relationships from Table 8 for Data from: (A) Guthrie, Oklahoma, for Blue Grass; (B) Guthrie, Oklahoma, for Cotton; (C) Holly Springs, Mississippi, for Corn; and (D) Madison, South Dakota, for Corn.