ESTIMATION OF GREEN-AMPT CONDUCTIVITY PARAMETERS: PART II. PERENNIAL CROPS

X. C. Zhang, M. A. Nearing, L. M. Risse

ABSTRACT. *Type and density of vegetation play an important role in affecting water infiltration and altering effective hydraulic conductivity (K_e). To predict infiltration accurately, K_e must be adjusted according to the dynamic changes of the environmental conditions. Thus, adjustment of K_e for different conditions becomes a major task for application of physically based models such as the Green-Ampt equation. The objective of this study was to identify and examine the major variables which affect the adjustment of the Green-Ampt K_e and to develop an estimation procedure for perennial crops for use in the Water Erosion Prediction Project (WEPP) model. A total of 85 plot-years of data from 13 natural runoff plots at six locations were used. The average length of records in meadow for each management system was seven years. Crops included alfalfa, clover, bermuda grass, and brome grass. Cropping systems included both continuous meadow and rotation meadow. Measured soil, climate, slope, and management information was used to build all of the WEPP input files. An optimization program was written to obtain calibrated values of K_e for each of the selected events. The correlation analyses on these calibrated values showed that total effective surface cover, storm rainfall, and the product of the two were highly correlated to K_e under meadow conditions. Effective hydraulic conductivities estimated for row crops were multiplied by a factor of 1.81 for use in companion meadow conditions. The regression line between the mean optimized K_e and the mean predicted K_e fit the data well ($r^2 = 0.82$). The new equation performed well in predicting both event and annual runoff. The r^2 of the regression between predicted and measured total runoff from all the selected events was 0.94 and the slope was 1.01. Model efficiency, calculated on an event basis, averaged 0.52 for seven of nine data sets, while negative values of model efficiency were obtained for the two data sets from the Geneva, New York, site. The r^2 and slope of the regression between predicted and measured annual runoff were 0.88 and 1.02, respectively.*

Keywords. *WEPP, Hydraulic conductivity, Green-Ampt equation, Runoff prediction, Perennial crops.*

Hydraulic conductivity continuously responds to changes in the environmental conditions of the natural system. Therefore, to obtain accurate infiltration predictions with process-based infiltration models such as the Green and Ampt (Green and Ampt, 1911), a procedure for adjusting the hydraulic conductivity to account for temporal changes in the soil surface conditions as well as the physical conditions of the soil matrix must be developed. This can be realized by calibrating or optimizing the hydraulic conductivity in the model equation with measured data.

The Green-Ampt equation is used to predict infiltration in the Water Erosion Prediction Project (WEPP) model. The general form of the equation is:

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

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:

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

where

η_e = effective porosity

θ_i = initial water content (mm^3/mm^3)

Ψ_f = average wetting front capillary potential (mm)

Parameterization of K_e and Ψ_f for various conditions is critical to obtaining accurate estimates of infiltration when using this equation. Ψ_f can be calculated from Brook and Corey's pore size index and bubbling pressure (Rawls et al., 1983), and also from basic soil properties as used in WEPP (Brakensiek, 1977; Rawls et al., 1989).

K_e is dependent not only on soil properties but also on crop management. Bare soil surfaces exposed to raindrop impact are susceptible to soil sealing and crusting. The degree of soil crusting depends on both soil properties and management practices. Risse et al. (1995) recently developed the following equation to compute K_e for bare conditions (K_{bare}) by accounting for the effects of crusting and tillage:

$$K_e = K_{bare}$$

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

where

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K_b = baseline hydraulic conductivity (mm/h) and is defined as the maximum hydraulic conductivity which occurs under freshly tilled and noncrusted conditions

CF = crust factor that can be calculated from basic soil properties (Rawls et al., 1990)

C_s = soil structure stability factor and can be estimated from soil properties (Risse et al., 1995)

E_a = cumulative kinetic energy of rainfall since last tillage (J/m^2)

rr = random roughness (cm)

Crop management and tillage practices affect both surface cover and soil physical properties such as porosity and pore size distribution. Surface cover is effective in reducing soil sealing and crusting, and therefore increases water infiltration (Mannering and Meyer, 1963). Since the susceptibility of the soil to crusting varies with soil properties, the effectiveness of surface cover in increasing infiltration is also influenced by soil properties. It is expected to be more pronounced on easily crusted and less stable soils. Canopy cover is effective in reducing surface runoff, but to a lesser degree than surface cover due to the canopy height effect (Khan et al., 1988). Additionally, surface and canopy cover has a positive interaction with rainfall characteristics on influencing water infiltration (Rawls et al., 1991; Wischmeier, 1966). More importantly, the accumulation of organic matter on the soil surface and less tillage disruption under meadow conditions improve soil aggregation (Stallings, 1953) and preserve existing macropores. All these findings should be considered in the development of a robust K_e adjustment equation for use in meadow conditions.

Analyses conducted on 328 plot-years of data from natural runoff plots at 8 locations showed that storm rainfall, total surface cover, and the interaction of the two were strongly related to K_e under row-cropped conditions (Zhang et al., 1995). An interactive term consisting of soil properties, storm rainfall, and total surface cover was developed and used in the following equation which predicts K_e for row-cropped conditions:

$$K_e = K_{bare}(1 - SC_{ef}) + (0.0534 + 0.01179 \times K_b) \times P \times SC_{ef} \qquad (4)$$

where K_{bare} and K_b are as defined above, P is the storm rainfall amount, and SC_{ef} is the total effective surface cover and is computed by:

$$SC_{ef} = C_{ef} + G(1 - C_{ef}) \qquad (5)$$

in which G is the residue cover, and C_{ef} is the effective canopy cover which is defined as:

$$C_{ef} = C \times C_h \qquad (6)$$

where C is the canopy cover, and C_h is the correction factor for canopy height effect and is calculated by:

$$C_h = e^{-0.336h} \qquad (7)$$

in which h is the average fall height (m) and is calculated as one half of canopy height in WEPP.

Wischmeier (1966) analyzed nearly 5,000 plot-years of data and found that runoff from row crops averaged 12% of total rainfall, while that from perennial crops averaged only 7%. This indicates that type and density of vegetation have a significant impact on water infiltration. The purpose of this study was to identify major parameters affecting the temporal adjustment of the Green-Ampt K_e for perennial crops and to develop an estimation equation for use in these conditions.

MATERIALS AND METHODS

RUNOFF DATA

Data from 13 natural rainfall plots at six sites were used to develop a K_e adjustment for the meadow conditions (table 1). The sites are the same as those used for the row crop adjustment equation (Zhang et al., 1995) except the Madison and Presque Isle sites were excluded due to the lack of perennial crop plots. Thus, the same climate, slope, and soil WEPP input files were used for the daily simulation. The average length of records in meadow for each data set was approximately seven years. A total of 85 plot-years of data with 505 measured runoff values which are independent of those used for row crops were used in this study.

The WEPP management input file for each crop was compiled according to the recorded data from the site records. Plant growth parameters in WEPP were calibrated to obtain a realistic above-ground biomass according to either the measured yields or an average yield level for the site. Perennial crops included alfalfa, clover, bermuda grass, and brome grass. Cropping systems included continuous meadow and rotation meadow (table 1). For the continuous meadow, tillage practices were seldom used during the period of study. For the rotation meadow, several tillage operations such as field cultivation were employed during the growing season on a few sites, while intense tillages including moldboard plow and disk were conducted during seedbed preparation prior to grass planting and/or after the rotation meadow. As for rotation row crops, conventional management practices were used. Moldboard, disk, and harrow were utilized for seedbed preparation, and a row cultivator for field cultivation.

To minimize the climate parameter-induced error in K_e optimization, the four key parameters (daily rainfall amount, rainfall duration, time to peak intensity, and ratio of peak to average intensity) were directly determined from breakpoint data for each event and used in the WEPP climate input file. Remaining parameters such as solar radiation, wind speed, and dew point temperature were generated by CLIGEN (climate generator, Nicks et al., 1993) for each site. However, the results of optimized K_e

Table 1. Background information of the data sets used in the study

Site	Crop Management	Number of Replicates	Periods Used	Years in Meadow	Number of Events Used
Hollysprings, Miss.	bermuda-corn-bermuda	2	1962-1968	5	104
Morris, Minn.	brome grass-corn-oats	3	1962-1971	4	18
Watkinsville, Ga.	corn-bermuda-bermuda	2	1961-1967	4	44
Bethany, Mo.	cont. alfalfa	1	1931-1940	10	83
	cont. brome grass	1	1931-1940	10	79
Geneva, N.Y.	cont. red clover	1	1937-1941	5	19
	cont. brome grass	1	1937-1946	10	30
Guthrie, Okla.	cont. bermuda grass	1	1942-1956	15	96
	wheat-clover-cotton	1	1942-1956	5	32

using these derived parameters may be slightly different from those using actual breakpoint data.

The field plots (22 × 4 m) were standard USLE natural rainfall plots. The slopes of the plots were nearly uniform and ranged from 0.05 to 0.08 m/m. In the WEPP soil input file, K_b for the infiltration layer of the top 20 cm was obtained by optimizing equation 3 for the fallow plot runoff data; the results are given in table 2. The saturated hydraulic conductivities for the underlying soil layers were calculated using the equations developed for the Erosion Productivity Impact Calculator (EPIC) model (Sharpley and Williams, 1990). The parameters such as sand and clay contents, percent organic matter, cation exchange capacity, and initial bulk density were obtained from the available measured data (table 2). To allow adequate root growth, the thickness of soil profile used on each site was greater than 1.5 m.

A series of storm events was carefully selected for each cropping system. Events with daily minimum temperature above 0° C, measured rainfall with breakpoints, and reliable runoff were used. Multiple rains during one day or a single rain which occurred over multiple days were excluded. Six to 12 of the largest storms with no measured runoff were added to each event file to eliminate bias in the data set. The total runoff from the selected events accounted for more than 70% of the total rainfall runoff. The average runoff volume of each event from all of the replicate plots was used in data analyses. These runoff values were compared with the model predicted values.

DATA ANALYSES

A program was written to optimize Green-Ampt K_e for each individual event. The objective function was least square error (LSE) which is the square of the difference between measured and predicted runoff. The objective function was minimized by iteratively varying K_e without changing the initial value of N_s in the WEPP infiltration subroutine. For each selected event, optimized K_e was obtained when the minimum LSE was reached. For most events, the LSE was reduced to near zero. However, due to saturated conditions in the upper soil layer, the LSE was greater than zero for a few events.

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

$$ME = 1 - \sum(Y_{obs} - Y_{pred})^2 / \sum(Y_{obs} - Y_{mean})^2 \quad (8)$$

where

Y_{obs} = measured storm runoff depth (mm)
Y_{pred} = model predicted storm runoff depth (mm)
Y_{mean} = mean measured storm runoff depth (mm)

The ME values 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 regression procedures in SAS were used to screen the major factors affecting K_e and to develop a correction factor for adapting equation 4 for use under meadow conditions.

RESULTS AND DISCUSSION

VARIABLES AFFECTING K_e ADJUSTMENT FOR PERENNIAL CROPS

A correlation analysis was conducted to examine the relationship between the selected variables and optimized K_e for perennial crops (table 3). In general, the correlation coefficients of perennial crops were much higher than those of row crops for all the selected variables except for buried residue mass, but the key variables which affect K_e adjustment were the same for perennial crops as for row crops (Zhang et al., 1995). The product of rainfall amount and total effective surface cover, PC, exhibited the highest overall correlation coefficient. It was followed by rainfall amount (P), total effective surface cover (SC_{ef}), and residue mass (G). The similarities in the correlation results for both row and perennial crops reveal that processes affecting K_e adjustment and infiltration were the same for perennial crops as for row crops.

Among the variables related to surface cover, C, G, and SC_{ef} were all strongly correlated with the optimized K_e values. The correlation coefficients obtained from the pooled data increased in the following order: C, G, and SC_{ef}. This sequence is basically in agreement with the conclusions made by other studies in the literature (Wischmeier and Smith, 1978; Khan et al., 1987). It is known that residue cover is more effective in reducing soil crusting and increasing infiltration than canopy cover due to canopy height effect. Both residue cover and canopy

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
Morris	Bames	l	17.65	1.30	0.260	39.4	23.2	3.37	18.4
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	l	5.31	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; l, loam; scl, sandy clay loam; fsl, fine sand loam.
† Obtained by optimizing equation 3 for fallow plots.

Table 3. Correlation coefficients of selected variables to optimized event hydraulic conductivities under meadow conditions*

Site	Canopy Cover (C)	Residue Cover (G)	Total 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	0.32	0.26	0.38	0.20	0.30	0.36	0.39	0.32	0.57
Morrris	0.30	0.42	0.41	0.36	0.11‡	0.37	0.34	0.68	0.53
Watkinsville	0.37	0.32	0.45	0.24	0.29	0.41	0.33	0.35	0.41
Bethany	0.36	0.12	0.29	0.07‡	0.06‡	0.27	0.17	0.51	0.56
Geneva	0.16‡	0.32	0.30	0.24	0.04‡	0.24	0.32	0.69	0.62
Guthrie	0.33	0.54	0.56	0.44	0.11‡	0.53	−0.08‡	0.51	0.74
Pooled§	0.21	0.35	0.36	0.28	0.03‡	0.34	0.29	0.43	0.55

* Data from the corresponding fallow plots were included in the test (Zhang et al., 1995).

† $PC = P \times SC_{ef}$.

‡ Not significant at 5% level.

§ Using the lumped database from all the sites.

cover are effective in increasing infiltration. The combination of the two enhances the effectiveness but the results are not additive. This is clearly shown by the SC_{ef} variable for which the correlation coefficient was greater than either C or G but smaller than the summation of the two. Residue mass on ground provided a similar but weaker correlation to optimized K_e as compared to G. Residue cover, though being internally calculated from residue mass, showed a stronger correlation to K_e than did the residue mass.

As compared to row crops (Zhang et al., 1995), buried residue mass was rather poorly related to K_e at most sites except for Hollysprings and Watkinsville where row crop residue prior to rotation meadow was turned under. On the rest of the sites, buried residue was extremely low because residue from rotation row crops was removed prior to rotation meadow, and no tillage operations were practiced to turn residue under during the years when meadow was grown. In contrast, total root mass (live plus dead) was closely related to K_e at all sites. The stronger interrelation between root mass and K_e for perennial crops than for row crops could be explained by the difference in root density (root length per unit soil volume). Higher root density for perennial crops as compared to row crops would be more effective in stabilizing soil aggregates and in formation of macropores. Days since last tillage, as an indicator of macropore development, showed a significant correlation to K_e ($\alpha = 0.05$) on five of the six sites. Again, the relationship was much stronger for perennial crops than for row crops. This indicates that macropore flow played a more important role in conducting water under meadow conditions, because less tillage disruption and high root density would have preserved and formed more macropores under these conditions. But the linear relationship might not be suitable at the Guthrie site since no tillage operations were performed during the 15-year period used in this study. One may expect that macroporosity may increase rapidly as "days since last tillage" increases at the beginning, and then may gradually level off when it approaches its "maximum". Based on this speculation, the correlation coefficient will decrease as no-till-days continues to increase above a certain level. Mathematical transforms of the data were not attempted for the site here. Although both total root mass and days since last tillage were significantly correlated to K_e (table 4), they were not used in the K_e adjustment equation along with SC_{ef} because of their significant interrelations to SC_{ef} ($\alpha = 0.05$). Total root mass was positively correlated to surface biomass which was also correlated to both canopy cover and residue cover. Days since last tillage directly affected the residue accumulation on the soil surfaces.

As for the case with row crops (Zhang et al., 1995), rainfall amount was positively correlated to K_e for perennial crops. It exhibited the second highest correlation coefficient among the variables studied. Such effects of rainfall characteristics on infiltration rate or hydraulic conductivity were also observed in several other studies (Rawls et al., 1991; Wischmeier, 1966). This might be explained by preferential flow phenomena. Generally, the proportion of water flow through macropores increases as water supply increases. As a result, the spatially averaged K_e value will be higher for larger storms under natural conditions. The effect of macropore flow on K_e was also reflected by the strong positive interactions between P and SC_{ef} (table 3). This is due to the fact that the high macroporosity formed by roots and soil fauna under agricultural management practices is often associated with a high plant and/or residue cover. The product of P and SC_{ef} (PC) provided higher correlation coefficients than SC_{ef} on five of the six sites and higher than P on four of the six sites. An overall test using pooled data showed that PC exhibited a much stronger correlation to K_e than either SC_{ef} or P alone as well. Thus, PC was considered to be the best variable for use in K_e adjustment.

ADJUSTMENT OF K_e FOR PERENNIAL CROPS

Since the correlation analyses showed that the same processes and key variables affect K_e adjustment for both row and perennial crops, equation 4 developed for row crops was used to compute the first approximation of K_e for each event under meadow conditions. The optimized K_e and calculated hydraulic conductivity (K_{eq4}) were used to

Table 4. Correlation coefficients among the selected variables under meadow conditions using pooled data set*

	Residue Cover (G)	Total Surface Cover (SC_{ef})	Total Root Mass (RM)	Days Since Last Tillage
C†	0.56	0.75	0.68	0.22
G		0.94	0.86	0.30
SC_{ef}			0.91	0.30
RM				0.29

* Data from the corresponding fallow plots were included in the analysis. All correlations are significant at $\alpha = 0.05$.

† Canopy cover.

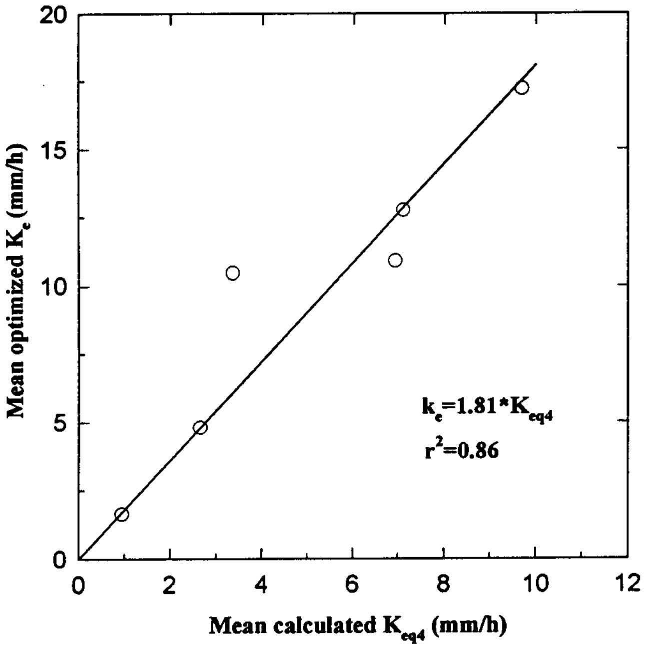

Figure 1–Mean optimized K_e vs. mean calculated K_e using equation 4 (K_{eq4}) for each site under meadow conditions.

develop an additional adjustment relationship. The mean optimized K_e and the mean calculated K_{eq4} on the six sites are plotted in figure 1. The following linear regression with zero intercept fit the data well as indicated by the r^2 of 0.86:

$$K_e = 1.81 \times K_{eq4} \tag{9}$$

K_{eq4} can be replaced by equation 4, yielding:

$$K_e = 1.81[K_{bare}(1 - SC_{ef}) + (0.0534 + 0.01179K_b) \times P \times SC_{ef}] \tag{10}$$

This equation indicates that with identical effective surface cover (SC_{ef}), the effective hydraulic conductivity of perennial crops is approximately 1.8 times that for row crops. Based on the measured runoff from rotation meadow, this equation should be used not only for continuous meadow but also for the first year meadow as long as canopy cover is established. This result basically agrees in trend with that drawn by Wischmeier (1966). He reported that runoff from row crops averaged 12% of total rainfall, while that from meadow averaged only 7%, showing that the overall runoff from row crops was about 1.7 times that from meadow.

The increased infiltration or hydraulic conductivity of perennial crops as compared to row crops can be explained by the following major factors. First, soil aggregation is better in meadow crops than in row crops. The soil aggregation increases as tillage intensity decreases and organic matter content increases. Wilson and Browning (1945) reported that the stability of soil aggregates increased in the following order: continuous corn, rotation corn, rotation oats, continuous alfalfa, and continuous bluegrass. Since soil aggregation was positively related to infiltration (Mannering et al., 1964; Logsdon et al., 1993; Jordahl and Karlen, 1993), the increase in soil aggregation would result in an increased infiltration rate. Wischmeier and Mannering (1965) found a positive correlation between infiltration and soil organic matter content. This is partially due to the fact that soil aggregation increases as organic matter increases. Stallings (1953) concluded that organic matter was more effective as an aggregating agent when utilized on the soil surface than when turned under, and the addition of easily decomposed organic matter could increase aggregation within a few days, with the maximum effect in about 20 to 30 days. Management practices used on perennial crops favor the accumulation of litter and residue on the soil surface, which results in a substantial increase in soil aggregation which in turn increases water infiltration.

Secondly, surface sealing and crusting reduce hydraulic conductivity dramatically. A dense vegetation cover, accompanied by a thick layer of litter and residue on the soil surface, is effective in controlling crust formation. Elimination of surface crusting can protect macropores at or near the surface from being blocked (Ela et al., 1992). Furthermore, the increased soil aggregation is expected to increase interaggregate macroporosity. Thirdly, biopores formed by roots and soil fauna are especially important in cropping systems using perennial crops. Meek et al. (1990) found that water flow in five-year-old alfalfa was mainly through the macropores. Finally, the dense network of root system could be useful in stabilizing soil structure and preserving existing macropores. In addition, preferential

Table 5. Total rainfall, optimized and predicted mean effective conductivities (K_e), and measured and predicted total runoff volumes for the selected events under meadow conditions

			K_e*		Total Runoff		
Site	Crop Management	Total Rainfall (mm)	Optimized (mm/h)	Predicted (mm/h)	Measured (mm)	Predicted (mm)	Model Efficiency† (ME)
Hollysprings	bermuda-corn-bermuda	3497	1.62	2.49	1196	1256	0.675
Morris	brome grass-corn-oats	646	12.15	17.55	27	17	0.649
Watkinsville	corn-bermuda-bermuda	1682	11.87	13.36	154	269	0.573
Bethany	cont. alfalfa	2900	6.40	4.98	310	553	0.293
	cont. brome grass	2761	5.47	5.90	308	265	0.466
Geneva	cont. red clover	549	6.71	6.54	35	54	xx
	cont. brome grass	1131	10.23	7.97	3	93	xx
Guthrie	cont. bermuda grass	3767	19.55	20.30	189	373	0.734
	wheat-clover-cotton	1270	13.81	22.19	112	145	0.275

* Means of all selected events.

† Calculated on an event basis; xx indicates a negative ME.

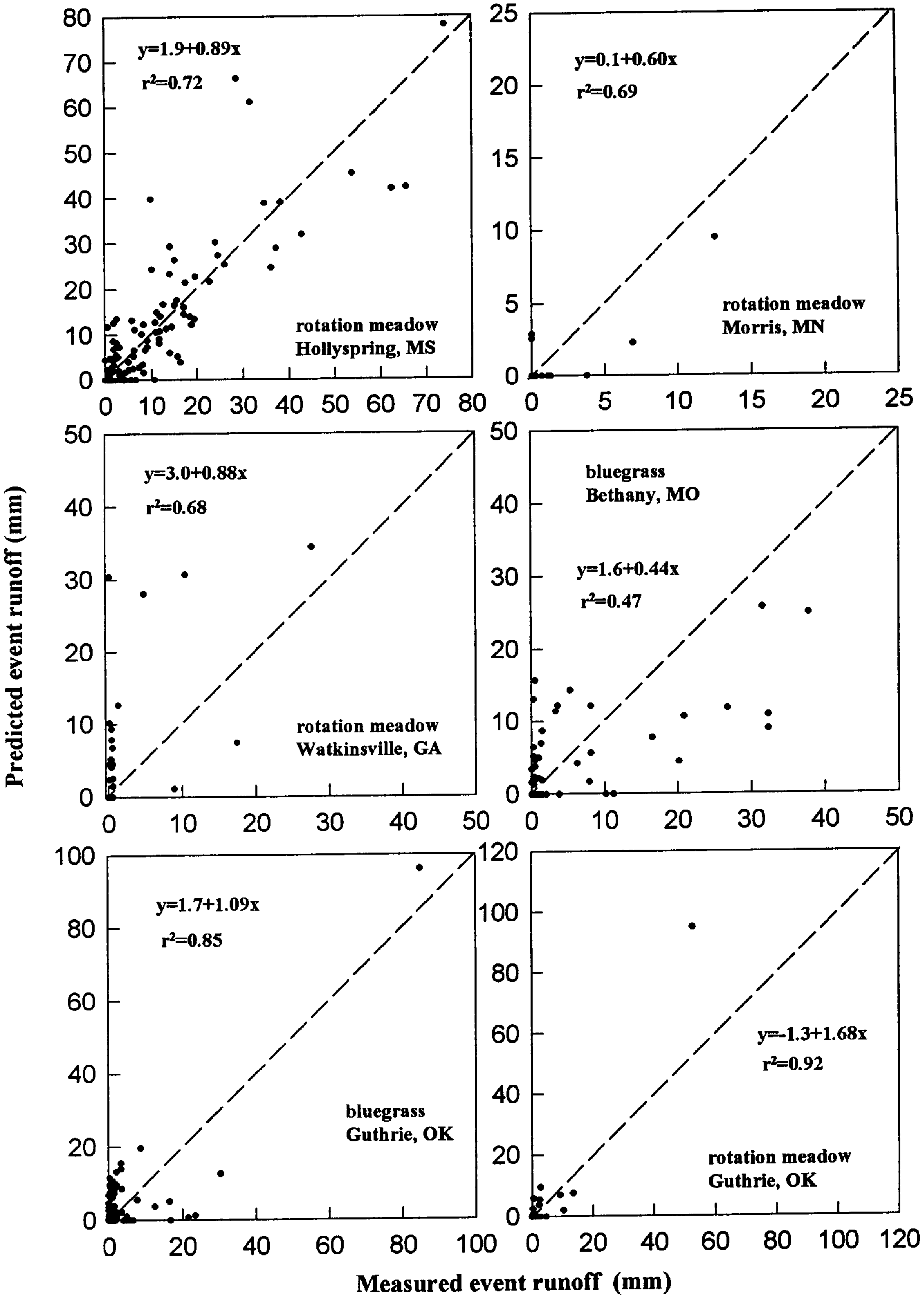

Figure 2–Plots of predicted vs. measured runoff for each individual storm for the selected data sets. Dash line is 1:1 line.

flow through either dead or living root channels (Reynolds, 1966) would further increase infiltration rate under meadow conditions.

PERFORMANCE OF THE EQUATION

Runoff and K_e were predicted using equation 10 in continuous simulation mode of WEPP. The mean optimized K_e for each management system agreed reasonably well with that predicted with the equation except for the Geneva site, where the predicted value was somewhat lower (table 5). Regression analysis showed that the coefficient of determination was 0.82 and the slope was 1.23 with the intercept being close to zero. The predicted total runoff from the selected events was somewhat higher than those of the measured for all the management systems except for continuous brome grass at the Bethany site, but the general trends agreed well. Linear regression between the predicted and the measured total runoff produced an r^2 of 0.94 and a slope of 1.01. Model efficiency, calculated on an event basis, is presented in table 5. Two negative ME values were obtained in the two sets of data from Geneva. At Geneva, only a small amount of measured runoff was observed, and the model generally overpredicted runoff. The same problem was also observed for row crops at this location. This consistent discrepancy might indicate that the K_b value obtained for this soil from fallow plots was a bit low for use in the cropped plots. The average ME without the two negative values was 0.52, indicating that the adjustment in equation 10 works well. The plots between predicted and measured event runoff for the six selected data sets along with linear regression results are shown in figure 2. The predicted runoff matched the measured runoff reasonably well. However, the regression showed that equation 10 tended to overpredict runoff for small events (positive intercept) and to slightly underpredict runoff for large events (slope less than one) on most occasions. This was also observed in the tillage and crusting adjustment for bare soil conditions (Risse et al., 1995). This may explain the reason why total runoff for most of the management systems was overpredicted (table 5). Since small rainfall events often outnumber the large events under natural conditions, the overprediction of numerous small events is often compensated by underprediction of a few large events.

The predicted rainfall-runoff values from all the events within a given year were summed to obtain the annual runoff. The results were compared to the measured data. Unlike the event-based analyses presented above, this type of analyses provided a method of including events which may have been excluded in the previous analyses due to one storm over multiple days or multiple storms within one day. The predicted and measured annual runoff volumes are plotted in figure 3 for all the years during which either continuous meadow or rotation meadow was grown. The predicted data matched the measured data well. Regression analysis indicated that the r^2 was 0.88 and the slope was 1.02. Again, the regression showed that the model tended to slightly overpredict runoff for the years with small runoff values and to underpredict runoff for the years with large runoff volumes.

The seasonal variations of K_e and runoff were investigated. The optimized and predicted K_e values from the selected events during five rotation meadow years at the Hollysprings site are plotted against Julian Day (time) in figure 4. Since the events were selected from five different rotation meadow years, variations of K_e between the adjacent data points might be due to the different crop management practices such as field cultivation, or to the storm size effect which is believed to be an important factor in instances when macropore flow dominates infiltration processes. The large values of optimized K_e

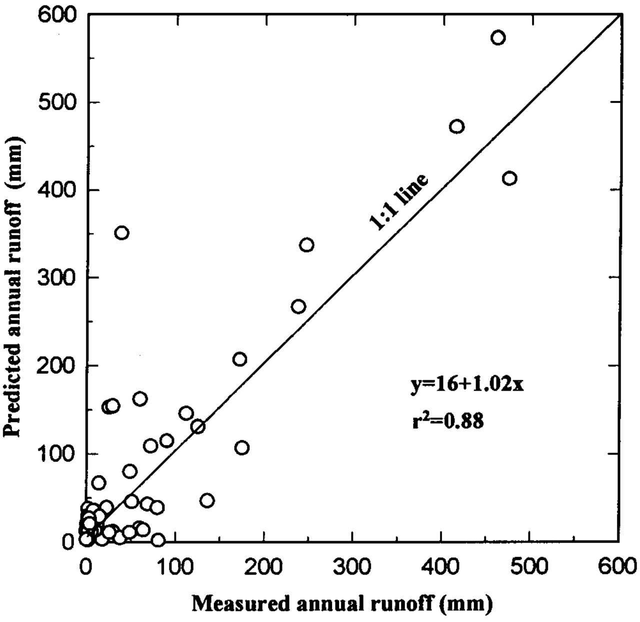

Figure 3–Model predicted vs. measured annual runoff volumes for years in meadow.

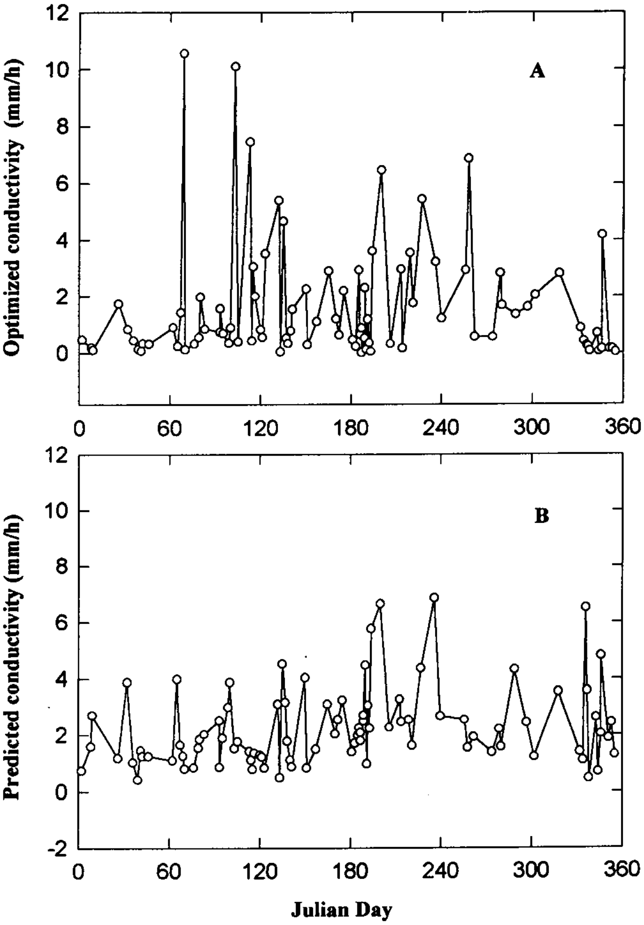

Figure 4–Seasonal variation of optimized and predicted event effective hydraulic conductivities during meadow years in a bermuda-corn-bermuda rotation at the Hollysprings site.

seemed to occur during the growing season when vegetation was dense and canopy cover was high (fig. 4a), while small values with less event-by-event variability appeared in the dormant period during which residue cover remained relatively low after late fall cuts. In comparison, the variation of optimized K_e values was represented to a certain degree by the predicted values (fig. 4b). Similarly, the measured and predicted event runoff values are plotted against Julian Day in figure 5. In contrast to optimized K_e values, the events with large runoff volumes occurred during the dormant period rather than in the growing season. The predicted event runoff volumes (fig. 5b) agreed well with the measured values (fig. 5a), indicating that the adjustment equation performs adequately. The similarities in trends between optimized and model predicted values indicate that seasonal variations of these variables are represented.

SUMMARY

The surface cover-related variables, C, G, and SC_{ef} were strongly correlated with K_e for meadow. The correlation coefficients from the pooled data increased in the following order: C, G, and SC_{ef}, indicating that SC_{ef} was a better predictor for representing the effects of surface cover on K_e.

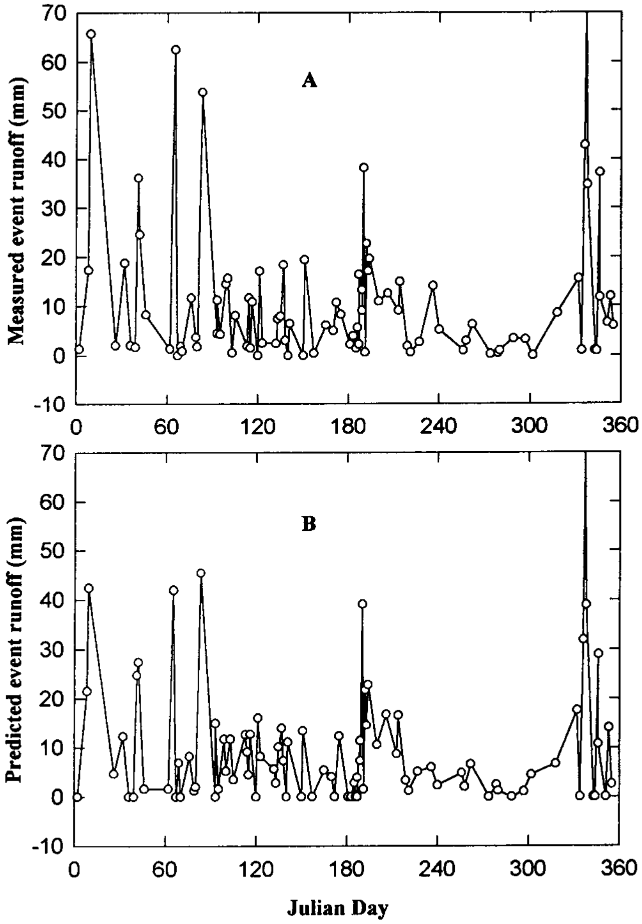

Figure 5–Seasonal distribution of measured and predicted event runoff during meadow years in a bermuda-corn-bermuda rotation at the Hollysprings site.

Residue biomass on ground was significantly correlated with K_e, but to a less degree than residue cover. For underground biomass, total root biomass was closely related to K_e, while buried residue mass was rather poorly related. Days since last tillage exhibited a good correlation with K_e. However, since all these variables were intercorrelated to SC_{ef}, they were not used in the K_e adjustment equation. More importantly, rainfall amount (P) showed the second best correlation to K_e of the variables studied, while the product of P and SC_{ef} provided the best.

Generally, the correlation coefficients for perennial crops were much higher than those of row crops for all the variables except for buried residue biomass. Perennial crops, which tend to form a thick layer of surface residue, are more effective in improving soil aggregation and in preserving macropores. However, the key variables which affect K_e prediction were similar for both perennial and row crops. Therefore, a correction factor was developed to adapt the equation derived for row crops for use in meadow conditions. The new K_e adjustment provided good predictions for both event and annual runoff. Regression between the measured and the predicted total runoff from all the selected events indicated that the r^2 was 0.94 and the slope was 1.01. Model efficiency averaged 0.52 for seven of nine data sets. For annual runoff, the r^2 and the slope between predicted and measured runoff with 68 years of data from the six sites were 0.88 and 1.02, respectively. In addition, the new equation tended to represent the seasonal variation of surface runoff.

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