ELSEVIER

Journal of Hydrology 169 (1995) 1–24

Journal of Hydrology

[1]

Variability in Green–Ampt effective hydraulic conductivity under fallow conditions

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

National Soil Erosion Research Laboratory, USDA-ARS, 1196 Soil Bldg., Purdue University, West Lafayette, IN 47905, USA

Received 17 June 1994; revision accepted 22 November 1994

Abstract

Hydraulic conductivity of the soil matrix dynamically responds to changes in the surrounding environment. Therefore, infiltration parameters for the Green–Ampt equation should change for each storm event in continuous simulation models. This study focused on improving Water Erosion Prediction Project (WEPP) model estimates of runoff using over 220 plot-years of natural runoff plot data from 11 locations. By optimizing the effective Green–Ampt hydraulic conductivity, K_e, for each event within the simulation, a method of correlating hydraulic conductivity on any given day to many other parameters was established. Factors with significant correlation to optimized values of K_e fell into three distinct categories; (1) factors related to soil crusting and tillage; (2) factors related to event size; (3) factors related to antecedent moisture conditions. Equations were developed to represent the temporal variability of hydraulic conductivity for each group. The equation describing the decrease in hydraulic conductivity owing to crusting used an exponential decay function based primarily on cumulative rainfall kinetic energy since last tillage, a soil stability factor, and a crust factor. The relationship between hydraulic conductivity and event size was characterized using an exponential relationship with total rainfall kinetic energy. The final adjustment used the moisture content immediately below the infiltration zone to account for the influence of antecedent moisture conditions on optimized hydraulic conductivities. All three adjustments were incrementally incorporated into WEPP and each improved the average model efficiency.

1. Introduction

Accurate infiltration components are essential to all process-based hydrologic or soil erosion models. Many current hydrologic models use some form of the

---

* Corresponding author at: Agricultural Engineering Department, University of Georgia, Athens, GA 30602, USA.

0022-1694/95/$09.50 © 1995 – Elsevier Science B.V. All rights reserved

SSDI 0022-1694(94)02676-9

Green–Ampt equation (Green and Ampt, 1911) to partition rainfall between runoff and infiltration. Although decades of use have confirmed the validity of this equation, accurate parameter estimates are required to obtain reliable results, as with all models. For single-event models measured parameters can be used; however, continuous simulation models often require both an accurate initial estimate as well as a method to adjust these parameters over the course of the simulation. These adjustments are intended to account for natural changes in soil structure such as consolidation and crusting as well as the effects of human-induced changes such as those associated with tillage.

In 1985, the USDA initiated the Water Erosion Prediction Project (WEPP) to 'develop a new generation of water erosion prediction technology' (Nearing et al., 1989). This new process-based model offers several advantages over existing erosion prediction technology. It has capabilities of predicting spatial and temporal distributions of net soil loss or net soil loss or gain for the entire hillslope for any period of time. It also has a wider range of applicability as it contains its own process based hydrology, water balance, plant growth, residue decomposition, and soil consolidation models as well as a climate generator and many other components that broaden its range of usefulness. A complete explanation of each of these components has been given by Lane and Nearing (1989).

Infiltration in WEPP is calculated using a solution of the Green–Ampt equation for unsteady rainfall developed by Chu (1978). It is essentially a two-stage process under steady rainfall. Initially, infiltration rate is equal to the rainfall application rate and after ponding occurs infiltration rate is calculated with the equation

$$f = K_e\left[1 + \frac{N_s}{F}\right] \tag{1}$$

where f is infiltration rate (in mm h^{-1}), N_s is effective matric potential (in mm), F is cumulative infiltration (in mm), and K_e is effective hydraulic conductivity (in mm h^{-1}). Effective matric potential is given by

$$N_s = (\eta_e - \theta_i)\psi \tag{2}$$

where η_e is availible porosity, θ_i is soil water content, and ψ is average wetting front capillary potential. Available porosity is calculated as the difference between total porosity corrected for entrapped air and antecedent water content. Average wetting front capillary potential is determined with an equation developed by Rawls and Brakensiek (1983), which states that

$$\psi = 0.01\mathrm{e}^{b} \tag{3}$$

where

$$b = 6.531 - 7.33\eta_e + 15.8Cl^2 + 3.81\eta_e^{\,2} + 3.4ClSa - 4.98Sa\eta_e + 16.1Sa^2\eta_e^{\,2} + 16Cl^2\eta_e^{\,2} - 14Sa^2Cl - 34.8Cl^2\eta_e - 8Sa^2\eta_e \tag{4}$$

and Sa and Cl are decimal amounts of sand and clay.

Whereas WEPP allows the user to input up to ten soil layers and uses these layers in the water balance component of the model, the infiltration routine uses a single-layer approach. The harmonic mean of the soil properties in the upper 200 mm are used to represent the effects of multilayer systems. Effective porosity, soil water content, and wetting front capillary potential are all calculated based on the mean of these soil properties.

Sensitivity analysis on the hydrologic component of WEPP has indicated that predicted runoff amounts are most sensitive to rainfall parameters (depth, duration, and intensity) and hydraulic conductivity (Nearing et al., 1990). Several other studies concluded that proper determination of hydraulic conductivity is critical to obtaining reliable estimates of runoff from WEPP (Van der Sweep, 1992; Risse et al., 1992; Risse, 1994). Current versions of WEPP allow for two methods of hydraulic conductivity input. In the first method, the user inputs an average effective value of hydraulic conductivity that remains constant throughout the simulation. Nearing et al. (1995) developed a procedure for estimating these average effective values based on soil properties, and Risse (1994) showed that this method produced reliable event estimates of runoff on natural runoff plots at 11 locations. The second method allows for temporal variation of hydraulic conductivity. In it, the user inputs a 'baseline' value of hydraulic conductivity that is then adjusted to account for temporal changes in effective hydraulic conductivity.

2. Objective

The objective of this project was to develop a set of equations to account for event-to-event variability in Green–Ampt effective hydraulic conductivities for use in the WEPP model under fallow conditions. This was accomplished using 220 plot-years of natural runoff plot data. The dominant processes affecting hydraulic conductivity under fallow conditions are tillage and soil crusting. As many of these plots had little or no cover, little emphasis was placed on the effects of residue or canopy. Interested readers are referred to Zhang et al. (1995) for a similar analysis on cropped plots.

3. Literature review

Soil crusting is one of the most influential processes in terms of reducing infiltration on a bare soil. Bradford and Huang (1993) presented one of the most recent and complete reviews of mechanisms affecting soil crust formation. They described the dominant factors as being rainfall characteristics, soil texture, slope steepness, aggregate stability, antecedent moisture content, surface roughness, and climatic variables. Tillage is important in relation to infiltration, as it removes the effects of surface crusts and alters surface roughness and plow layer porosity. When using infiltration models, there is a need to quantify the interactive effects of crusting and tillage on infiltration parameters. Rawls and Brakensiek (1983) presented a procedure for selecting Green–Ampt infiltration parameters that included the effects of management. They presented nomographs based on particle size distribution, organic matter, and bulk density that could be used to estimate the final hydraulic conductivity of a crust for any given event throughout the growing season. These nomographs would, however, be of little use to a continuous simulation model as they would be difficult to code and can only be applied to a single event.

Many other methods for predicting changes in hydraulic conductivity that reflect the effects of tillage, residue, and crusting have been investigated. Most of these studies have examined the effects of management on infiltration during single storm events. They are of limited use for predicting infiltration rates in continuous simulation models as they do not consider effects of previous rainfall and timing or frequency of tillage. Several researchers have worked on developing infiltration models that account for a crust. Most of these models define the soil crust as an additional soil layer in a multilayer system. Therefore, these models are less computationally efficient than the single-layer Green–Ampt infiltration model that WEPP uses.

Although Van Doren and Allmaras (1978) were primarily interested in the effects of residue on infiltration rates, they presented an equation for the conductivity of a soil surface layer in the form

$$K_t = K_b \mathrm{e}^{-\beta(1-\mathrm{cfrac})Ea} \tag{5}$$

where K_t and K_b are current and initial (freshly tilled) conductivity of the surface layer (m h^{-1}), Ea is kinetic energy of the rainfall since the most recent tillage (J m^{-2}), cfrac is the fraction of the soil surface covered by residue, and β is a structural stability constant of the soil (m^2 J^{-1}). Van Doren and Allmaras stated that the soil stability constant is an empirically derived value dependent on soil type, cropping history, and tillage history with values ranging from 0.00012 to 0.00117 m^2 J^{-1}. They also showed that this was a reasonable model for computing changes in conductivity with rainfall as influenced by residue and management practices. Eigel and Moore (1983) used the following equation to describe the effects of rainfall kinetic energy on infiltration:

$$f = f_t + (f_i - f_f)\mathrm{e}^{-\beta(Ea-Ea_{sp})} \tag{6}$$

where f_i, f_f and f are initial, final, and transient infiltration rates (mm h^{-1}), Ea and Ea_{sp} are cumulative rainfall kinetic energy and cumulative kinetic energy at the time of ponding (J m^{-2}), and β is a kinetic energy coefficient (similar to the soil stability factor of Eq. (5)). They found that β averaged 0.0356 for a Sadler–Belknap silt loam soil. Brakensiek and Rawls (1983) proposed an equation similar to that of Van Doren and Allmaras. Their equation stated that

$$K_t = K_f + (K_b - K_f)\mathrm{e}^{-C\mathrm{cfrac}(1-rr/4)Ea} \tag{7}$$

where K_t, K_f and K_b are the transient, the final, and initial crust hydraulic conductivity (mm h^{-1}), rr is the random roughness of the soil surface (mm), and represents the rapidity with which the crust conductivity declines from K_b to K_f. Although each of these equations was derived to represent changes in the crust hydraulic conductivity within a single event, they do present the parameters that may be important in predicting the effects of tillage and crusting on infiltration over a series of events for a single-layer representation.

Using a form of Eq. (7), Bosch and Onstad (1988) focused on determining the soil parameters that influence the rate of decline in hydraulic conductivity during crusting. They found that C ranged from 0.00038 to 0.00088 $\mathrm{m^2\ J^{-1}}$ for four medium-textured soils. Regression analysis also indicated that bulk density, percentage of silt, and percentage of sand were the primary soil factors influencing the rate of surface seal development.

Rawls et al. (1990) presented an equation for determining the effect of a crust on the hydraulic conductivity for the single-layer Green–Ampt equation that is used in WEPP. It defines a crust factor, CF, as

$$CF = \frac{K_e}{K_s} = \frac{SC}{1 + \psi/L} \tag{8}$$

where K_e and K_s are effective and subcrust hydraulic conductivities, SC is the correction factor for partial saturation of the subcrust soil, ψ is steady-state capillary potential at the crust–subcrust interface, and L is wetted depth. They also derived the following continuous relationships for SC and ψ:

$$SC = 0.736 + 0.0019(\%\ \text{sand}) \tag{9}$$

$$\psi = 45.19 - 46.68(SC) \tag{10}$$

The depth to the wetting front is calculated in WEPP as

$$L = 0.147 - 0.0015(\%\ \text{sand})^2 - 0.00003(\%\ \text{clay})\rho_b \tag{11}$$

where ρ_b is bulk density (kg $\mathrm{m^{-3}}$). If the calculated value of L is less than crust thickness (0.005 m in WEPP) then it is set equal to crust thickness. Rawls et al. (1990) used data from 36 covered and uncovered plots to show that this method could provide reasonable estimates of crusted hydraulic conductivities based on freshly tilled hydraulic conductivities. Although this procedure provides a method for estimating crusted hydraulic conductivity based on initial or saturated hydraulic conductivity for freshly tilled conditions, it does not explicitly calculate the conductivity during crust development.

4. Materials and methods

4.1. Description of data set

Rainfall, runoff, and soil loss data were collected across the USA from the 1930s until the present in an effort used mainly to develop the Universal Soil Loss Equation (USLE). Approximately 10000 plot-years of this type data were obtained from the National Soil Erosion Research Laboratory. Of these, 21 plots at 11 locations were chosen to be used in this study (Table 1). All of the selected plots were in continuous cultivated fallow conditions so the effects of plant growth and residue cover on

Table 1
Selected natural runoff plots used in this study

Site	Years	Slope (%)	Replicates	No. of selected events	% of total measured runoff included
Bethany, MO	1931–1940	8.0	1	109	71
Castana, IA	1960–1971	14.0	2	90	86
Geneva, NY	1937–1946	8.0	1	97	48
Guthrie, OK	1940–1956	7.7	1	170	80
Holly Springs, MS	1961–1968	5.0	2	208	71
Madison, SD	1961–1970	5.8	2	60	86
Morris, MN	1961–1971	5.9	3	72	72
Pendleton, OR	1979–1989	16.0	2	82	34
Presque Isle, ME	1961–1969	8.0	3	99	72
Tifton, GA	1959–1966	3.0	2	72	61
Watkinsville, GA	1961–1966	7.0	2	110	63

infiltration could be neglected. The raw data were converted to input file format for continuous simulations with the WEPP model. For the plots with replicates, the model would produce the same estimate of runoff for each replicate. Therefore, average measured runoff was used rather than running the model for each replicate.

The measured climate data consisted of maximum and minimum temperatures and daily rainfall amounts. In addition, most storms that produced runoff also had detailed breakpoint data from tipping bucket rain gages. These data were used to calculate the rainfall durations, time to maximum intensity, and relative peak intensity. CLIGEN Version 2.3, the stochastic weather generator included with WEPP, was used to generate the remaining climate parameters including solar radiation, wind velocity and direction, and dew-point temperature. All of the plots were of nearly uniform slope with constant widths and could be represented with a single overland flow element. They were all of standard USLE natural runoff plot dimensions (4.05 m × 22.13 m) except for Tifton (8.10 m × 44.26 m) and Pendleton (4.05 m × 33.50 m) and were on the slopes given in Table 1. Information on the dates and types of tillage were obtained from the USLE database. The tillage data base included in WEPP documentation was used to obtain tillage parameters including the tillage depth, random roughness, tillage intensity, ridge height and ridge spacing for construction of management files. Weed and residue cover was assumed to be insignificant as each of these plots had been in continuous cultivated fallow condition for at least a year prior to the start of the simulation. Soil profile input files containing averaged measured data were compiled from a variety of sources, including the original USLE data sheets, experiment station bulletins, soil profile descriptions obtained from the Soil Conservation Service, and the Soils 5 database. Approximately three to five soil layers were used for each profile description. The hydraulic conductivity in the top soil layer was calibrated to measured data using an algorithm described by Risse et al. (1994) that minimized the least-squares error between measured and predicted runoff volumes for a series of events. The hydraulic conductivity for the soil layers beneath the infiltration zone (0.2 m), which have little effect on infiltration but are used for water balance calculations, were calculated using equations developed for the Erosion Productivity Impact Calculator (EPIC) model (Sharpley and Williams, 1990). Table 2 lists the soil properties for the upper soil horizon at each site.

4.2. Calibration algorithm

A calibration algorithm was developed to determine the optimum effective hydraulic conductivity for each event. To automate the calibration procedure, selected events and their corresponding values of runoff were input into an 'events' file. Most events were included in this file; however, at times, measured events had to be excluded for the following reasons: (1) gross differences in runoff produced on replicated plots that seemed to indicate a measurement error; (2) no breakpoint rainfall data were available to calculate the disaggregated rainfall parameters; (3) measured runoff was less than 1 mm; (4) the entire period of rainfall and subsequent runoff had taken place over several days or many storms contributed to a single measurement of runoff; (5) the storm occurred during a period when there was snow on the ground or the soil or air temperature was below freezing during the event. To prevent any bias in the data set, events where WEPP predicted significant runoff (over 3 mm) were included even if there were no measured values. Table 1 lists the number of events that were used at each location. The high percentages of runoff data indicates that at most sites most of the data were included. Sites with lower values had many more events that occurred during winter.

The optimization program was written by inserting additional code into the subroutine containing the Green–Ampt equation in WEPP. A flag was used to

Table 2
Input soil properties of the upper soil layer at each location

Site	Soil	Texture[a] class	Av. K_e [b] (mm h^{-1})	Sand (%)	Clay (%)	Organic matter (%)	CEC (cmol kg^{-1})
Bethany	Shelby	sil	1.22	27.8	29.0	3.03	16.5
Castana	Monona	sil	2.04	7.1	23.5	2.00	20.1
Geneva	Ontario	l	2.27	44.2	14.9	4.50	11.8
Guthrie	Stephenville	fsl	6.19	73.2	7.9	1.60	7.2
Holly Springs	Providence	sil	0.31	2.0	19.8	0.81	9.3
Madison	Egan	sicl	1.80	7.0	32.2	3.70	25.1
Morris	Barnes	l	7.68	39.4	23.2	3.37	18.4
Pendleton	Thatuna	sil	0.51	28.0	23.0	4.30	16.2
Presque Isle	Caribou	gr sil	2.38	38.8	13.7	3.76	13.2
Tifton	Tifton	sl	7.78	87.0	5.7	0.70	4.1
Watkinsville	Cecil	scl	4.41	66.5	19.6	0.89	4.8

[a] sil, Silt loam; sicl, silty clay loam; gr, gravelly; l, loam; sl, sandy loam; fsl, fine sandy loam; scl, sandy clay loam.

[b] Calibrated value of average effective hydraulic conductivity from Risse et al. (1994).

determine if the storm on a given day was one of the chosen events. If it was not, then WEPP proceeded as normal using the hydraulic conductivity from the soil input file. If it was, then hydraulic conductivity was manipulated until predicted runoff was equal to measured runoff and this value was printed to an output file. This value would represent the optimized effective Green–Ampt hydraulic conductivity (K_{opt}) for the given event. The remainder of the WEPP parameters such as moisture content and matric potential were unaffected by this process. In most cases, the value of K_e could be manipulated so that predicted runoff was nearly identical to average measured runoff for the event. For approximately 5% of the events measured and predicted runoff differed by more than 0.5 mm. For these events the value of K_e that minimized the error was selected. After the calibration program was run, a database was established that contained the event K_{opt} as well as the values of many other parameters. The daily values for each of these other parameters were obtained from WEPP output files following the simulation. Correlation analysis was then used to determine the strength of the relationship between the effective conductivity and each of these parameters.

Nash and Sutcliffe (1970) introduced a term called model efficiency that was used to evaluate the goodness of fit between model predicted and measured outputs. It is defined as

$$ME = 1 - \frac{\sum(Y_{\mathrm{obs}} - Y_{\mathrm{pred}})^2}{\sum(Y_{\mathrm{obs}} - Y_{\mathrm{mean}})^2} \tag{12}$$

where ME is model efficiency, Y_{obs} is measured output, Y_{pred} is output predicted by the model, and Y_{mean} is the mean measured output for all events. In many cases, the model efficiency is similar to the coefficient of determination (r^2); however, the residual variation is calculated using the mean of actual observations rather than values from the best regression line between observed and predicted values. This is an important difference because it shows that model efficiency is comparing the predictions to the one-to-one line rather than the best regression line through the points. If model results are highly correlated but biased, then model efficiency will be lower than the coefficient of determination. Much like the coefficient of determination, a value of one indicates perfect agreement between measured and predicted values and decreasing values indicate less correlation. The value of model efficiency may be negative. If this occurs it indicates that the average measured value is a better estimate than the model prediction.

5. Results and discussion

5.1. Analysis of factors influencing K_{opt}

Table 3 lists results of correlation analysis between event values of K_{opt} and three groups of parameters that displayed significant correlation to the effective hydraulic conductivities. Several parameters such as month or season of the event, Julian day

Table 3
Correlation of several significant parameters to event effective conductivities

Parameter	Average correlation coefficient[a]	No. of sites with significant correlation[b]	Other parameters to which it is correlated[c]
Group 1: Parameters associated with soil and tillage			
por – porosity of infiltration zone	0.31	6	All
bd — bulk density in infiltration zone	−0.31	6	All
rr — random roughness of surface	0.21	2	All except ftlt
rh — ridge height on surface	0.29	5	All
rfcum — total rainfall since last tillage	−0.23	5	All
kecum — total KE of rain since last tillage	−0.22	5	All
ftlt — freeze/thaw cycles since last tillage	−0.05	1	All except *rr*
Group 2: Parameters associated with event size			
KE — kinetic energy of rainfall	0.42	10	All
WRO — WEPP predicted runoff	0.40	10	All
Rn — rainfall depth	0.39	10	All
Dur — duration of rainfall	0.22	5	All
ip — dimensionless peak rainfall intensity	0.21	4	All
pint — peak rainfall intensity	0.19	2	All
Group 3: Parameters associated with antecedent moisture			
str — available storage in infiltration zone	0.33	6	All except *sm*
sw — soil water in infiltration zone	−0.31	6	All except 3*dr* and 5*dr*
*sw*1 — soil water in soil layer 1	−0.24	4	All
*sw*2 — soil water in soil layer 2	−0.26	6	All except *sw*3
*sw*3 — soil water in soil layer 3	−0.31	7	All but *sw*2, 5*dr*, and 3*dr*
5*dr* — rainfall in 5 preceding days	−0.29	6	All but *sm*, *sw*3, and *sw*
3*dr* — rainfall in 3 preceding days	−0.25	5	All but *sm*, *sw*3, and *sw*
sm — matric potential of infiltration zone	0.18	2	*sw*, *sw*1, *sw*2, *sw*3
avstr — difference between rainfall and storage	−0.09	1	*sm*

[a] Average of the correlation coefficients for the event K_es to the parameter in question.
[b] Number of sites where this parameter was significantly correlated to K_e at the 0.01 level.
[c] Other parameters within the given group to which this parameter was significantly correlated at the 0.01 level.

into the simulation, dimensionless time to peak rainfall intensity, and days since last tillage were not significantly correlated (at the 0.01 level) to the effective conductivities at any of the sites. The variables that did exhibit significant correlations for at least one of the sites were placed into three distinct groups based on the primary mechanisms thought to control the way they affect K_e and their correlations with each other.

The first group of parameters included all of those that were affected by tillage. These are the primary factors that could be used to develop a method to predict the effects of crusting and surface sealing on conductivity. Soil porosity is calculated from bulk density and therefore both of these parameters had identical correlation coefficients. In WEPP, changes in bulk density due to rainfall and consolidation are based on rainfall and number of days since the last tillage operation. Changes in both random roughness and ridge height are also calculated based on the amount of rainfall since the last tillage operation. Therefore, all of these parameters were significantly correlated to each other as well as to the kinetic energy associated with rainfall since the last tillage. Number of freeze–thaw cycles since the last tillage was also included, as cyclic freezing and thawing of the soil surface has been shown to disrupt significantly an established surface seal and increase greatly the conductivity. Although the number of freeze–thaw cycles did not appear to be a significant parameter, this was probably because over 90% of the events did not experience any freeze–thaw cycles between tillage operations.

The second group of parameters dealt with the size and intensity of the event. In terms of significance, these parameters generally exhibited the highest overall correlation coefficients, and three of the parameters, total predicted runoff, rainfall depth and kinetic energy, exhibited significant correlation at ten of 11 sites (none were correlated at Madison). These parameters primarily affect infiltration through the amount of crusting that occurs during the storm. They also have a profound effect on other variables, such as time to ponding and depth of the ponded water on the surface, that may not be adequately modeled in WEPP. Perhaps more importantly, these parameters may be exhibiting deficiencies of the Green–Ampt equation. The Green–Ampt equation, as used in WEPP, assumes a homogeneous soil profile with a sharp and well-defined wetting front. However, if the rainfall distribution includes periods of low-intensity rainfall or has longer durations, as is often the case for larger events, the wetted profile will redistribute and the Green–Ampt equation will not be reliable at later times (Skaggs and Khaleel, 1982). This deficiency will be reflected in the optimized values of K_e, as it is forced to fit the assumptions of the Green–Ampt equation even if they have been violated. Another possible explanation for the high correlation that these parameters exhibited could lie in the method that CLIGEN, the weather generator included in the WEPP model, uses to disaggregate rainfall. Because WEPP simulates all storms as single-peak events with an increasing and decreasing exponential distribution, the rainfall distribution may not accurately portray the actual distribution even though the rainfall durations, amounts, and peak intensities were calculated from measured data.

The final group of parameters consisted of all measurements of soil moisture conditions preceding the event. The initial water content is important in terms of infiltration, as a drier soil will have a higher hydraulic gradient and available storage volume than a wet soil. The Green–Ampt equation is designed to account for initial water content through the effective matric potential term; however, this is dependent on the water balance component of WEPP providing reliable estimates of water content. Of the soil water terms tested, available storage (difference between total porosity and soil water content in the infiltration zone) exhibited the highest correlation coefficient. Because the infiltration zone is composed of the upper two soil layers in WEPP, effects of soil water in either of the first two layers or their sum are assumed to be exhibited in this storage term. The fact that these parameters were all significantly correlated to each other is evidence of this assumption. A somewhat surprising result was the fact that the amount of soil water in the layer directly beneath the infiltration zone was more highly correlated than the amount of soil water in the infiltration zone. A possible explanation for this is that the matric potential term used in the Green–Ampt equation does not quantitatively account for soil water in this layer. Therefore, it appears to exhibit more correlation than soil water in the upper layers that are accounted for in the matric potential term. Conversely, it could indicate that either the depth of the infiltration zone needs to be extended or that a method of transferring soil water between layers during the event should be implemented.

5.2. Crusting adjustment

Although the parameters associated with tillage and crusting did not display as much correlation to the optimized effective hydraulic conductivities as some of the other variables, an equation for this adjustment was developed first, as it had been evaluated in several other studies. Other studies used either rainfall amount or total kinetic energy since last tillage to quantify the amount of crusting the soil surface will exhibit. In the development of this equation, the general form of the relationship proposed by Van Doren and Allmaras (1978), Brakensiek and Rawls (1983) and Eigel and Moore (1983) was selected. This can be simplified to

$$K_e = K_f + (K_b - K_f) \cdot f(\text{kecum}, \text{rfcum} \ldots) \tag{13}$$

where K_e is effective conductivity for any given event (mm h^{-1}), K_b and K_f are baseline and fully crusted hydraulic conductivities, and f is some function of either rainfall or kinetic energy since last tillage. K_b now represents the maximum hydraulic conductivity. K_e decreases at a rate proportional to the function f until it reaches the fully crusted or final value.

A method for estimating K_f was evaluated so that the user need not input two values of hydraulic conductivity. Allowing the maximum adjustment (MA) to equal K_f/K_b and rearranging Eq. (13),

$$TA = MA + (1 - MA) \cdot f(\text{kecum}, \text{rfcum} \ldots) \tag{14}$$

where $TA = K_e/K_b$ is a tillage adjustment factor ranging from the maximum adjustment to one. The maximum adjustment factor is then equivalent to the crust factor (CF) given by Rawls et al. (1990) and calculated using Eqs. (8)–(11). Table 4 compares the crust factor developed by Rawls et al. (1990) with two alternate methods of calculating the maximum adjustment. In the first method, MA was calculated as the average K_e for all of events with less than 1 mm of rainfall since the last tillage operation divided by the average K_e for the ten events with the most rainfall since tillage. In the second method, the optimized value was determined by assuming that the decay function for the hydraulic conductivity was linear from zero to 100 mm of rainfall since last tillage and one when rainfall since last tillage exceeded 100 mm. SAS non-linear fitting routines were then used to optimize for MA and K_b in Eq. (14). The data in Table 4 indicate that the crust factor calculated by the equations of Rawls et al. (1990) can adequately predict the maximum reduction in conductivity related to crust formation. At six of ten sites, the calculated crust factor was within 10% of the maximum adjustment calculated from the data. At Bethany and Castana

Table 4
Comparison of values for maximum adjustment owing to crusting and tillage from three different methods

Site	Av. K_e for events with rfcum < 1.0	Av. K_e for 10 events with max. rfcum	MA calc. from K_f/K_b	MA optimum from regression	CF from Rawls et al. (1990)
Bethany	1.72	0.61	0.35	0.77	0.20
Castana	1.87	1.18	0.63	0.63	0.27
Geneva	4.35	1.85	0.42	0.27	0.37
Holly Springs	1.40	0.11	0.08	0.27	0.29
Madison	3.84	0.70	0.18	0.33	0.20
Morris	11.57	2.11	0.18	0.23	0.27
Pendleton	[b]	0.45	[b]	0.14	0.28
Presque Isle	4.13	1.18	0.28	0.16	0.38
Tifton	13.18	2.16	0.20	0.20	0.20
Watkinsville	8.13	2.73	0.20	0.55	0.20

[a] Gurthrie not included, as there was no tillage at this location.
[b] Pendleton had no events with less than 80 mm of rainfall since last tillage.

the reduction in hydraulic conductivity was not as significant as that predicted by the crust factor, and the data from Holly Springs indicated that the crust factor should have been slightly higher. Having established a method for calculating the maximum adjustment, the function for the decay in the hydraulic conductivity was investigated. Linear, exponential, and power functions using both rainfall and rainfall kinetic energy since last tillage were investigated. SAS non-linear analysis was used to determine best-fit values for K_b and other coefficients in the functions that produced the highest correlation coefficients. The following function, similar to that of Brakensiek and Rawls (1983) (Eq. (7)), provided the best overall results (Table 5):

$$K_e = K_b\left\{\frac{K_f}{K_b} + \left(1 - \frac{K_f}{K_b}\right)\exp\left[-C\cdot Ea\cdot\left(1 - \frac{rr}{4}\right)\right]\right\} \tag{15}$$

In general, exponential relationships provided a much better fit than linear relationships. At many of the sites, both the optimized baseline conductivity and the adjusted sum-of-squares value were nearly identical for exponential relationships involving rainfall or kinetic energy, indicating that either could be used. The relationship involving kinetic energy was selected as it performed slightly better and was more consistent in terms of the previous studies. Generally, rainfall energy rather than rainfall amount is thought to control the rate of surface seal formation. The fact that random roughness is included in this function did not alter the results significantly (average r^2 without random roughness was 0.56); however, this was probably because random roughness did not fluctuate much on these plots. This term is important as crust rarely forms on surfaces with random roughnesses greater than 40 mm and the reduction of effective hydraulic conductivity related to crust formation will generally be more significant on smoother surfaces (Rawls et al., 1990).

The coefficient, C, in Eq. (15) represents the rate at which the effective conductivity

Table 5
Comparison of three hydraulic conductivity decay functions

Site	Function							
	1: linear		2: exp. rfcum			3: exp. kecum		
	K_b	r^2 [b]	K_b	C	r^2 [b]	K_b	$C \times 10^3$	r^2 [b]
Bethany	2.40	0.25	1.54	0.001	0.43	1.54	0.06	0.44
Castana	4.28	0.48	2.22	0.004	0.62	2.22	0.20	0.62
Geneva	4.13	0.36	4.42	0.034	0.54	4.37	1.97	0.56
Holly Springs	0.57	0.46	1.08	0.339	0.45	1.09	0.86	0.45
Madison	3.26	0.56	3.46	0.754	0.64	3.30	0.73	0.63
Morris	15.63	0.55	12.51	0.047	0.76	12.65	3.40	0.77
Pendleton	1.53	0.82	0.93	0.019	0.43	0.94	1.50	0.43
Presque Isle	3.48	0.44	4.10	0.049	0.53	4.12	3.30	0.54
Tifton	15.45	0.43	15.00	0.065	0.61	15.93	11.80	0.60
Watkinsville	16.34	0.78	12.26	0.063	0.60	13.29	31.20	0.62
Average		0.51			0.56			0.57

[a] Functions:

1: $K_e/K_b = 1 - (1 - MA) \cdot \mathrm{rfcum} \cdot 0.01$ for rfcum < 100 mm; $K_e/K_b = MA$ for rfcum > 100 mm.

2: $K_e/K_b = MA + (1 - MA) \cdot \exp(-C \cdot \mathrm{rfcum})$ (rfcum in mm).

3: $K_e/K_b = MA + (1 - MA) \cdot \exp[-C \cdot \mathrm{kecum} \cdot (1 - rr/4)]$ (kecum in J m^{-2}, rr in cm).

[b] r^2 represents a non-linear relative adjusted least-squares error, and is calculated as sum of squares explained by the regression/uncorrected total sum of squares.

declines from K_b to K_f. It is much like the soil stability factor of Van Doren and Allmaras (1978) and the kinetic energy coefficient of Eigel and Moore (1983). Values obtained by fitting Eq. (15) to the optimized effective conductivities ranged from 0.00006 to 0.0312 m^2 J^{-1}. This generally agreed with the range of values reported in the literature (0.00012–0.0356) except for the lowest value. This value (0.00006) was measured at Bethany, where the value of MA indicated that the reduction in conductivity owing to soil crusting was relatively minor. For this equation to be widely applicable, the user must have a method for obtaining accurate values of C because few measured values are readily available. Soil factors that exhibited the most correlation to optimized C values were percentage of sand ($r = 0.68$), bulk density ($r = 0.66$), and percentage of silt ($r = -0.72$). Bosch and Onstad (1988) found similar results. The following equation was developed using stepwise linear regression to relate the soil stability factor to selected soil properties:

$$C = -0.0028 + 0.000113Sa + 0.00125\frac{Cl}{\mathrm{CEC}} \tag{16}$$

where Sa and Cl are percentage of sand and clay, and CEC is cation exchange capacity. This equation had an r^2 of 0.95 when fitted to C values reported in Table 6. Bounds of $0.0001 < C < 0.01$ were imposed on this equation to prevent negative C values on soils with very low sand and clay contents. Using this equation, soils with high amounts of sand or clay and a low CEC would form a crust more rapidly.

Table 6
Predicted soil stability coefficients (C) and corresponding values of r^2 using these calculated values

Site	Optimum C	Calculated C	$r^{2\,a}$
Bethany	0.0001	0.0025	0.35
Castana	0.0002	0.0001	0.61
Geneva	0.0020	0.0038	0.54
Holly Springs	0.0009	0.0001	0.45
Madison	0.0007	0.0001	0.57
Morris	0.0034	0.0032	0.77
Pendleton	0.0015	0.0021	0.43
Presque Isle	0.0033	0.0029	0.52
Tifton	0.0118	0.0088	0.60
Watkinsville	0.0312	0.0098	0.62

[a] r^2 is non-linear sum of squares regression/sum of squares total.

Eq. (16) provided estimates of C that were within one order of magnitude of the optimized values for eight of the ten sites. Over all sites, estimation of C values as opposed to optimizing them only reduced the average non-linear r^2 value from 0.57 to 0.55 (Table 6).

Fig. 1 shows optimized event conductivities plotted against those calculated using the tillage adjustment with an optimized baseline hydraulic conductivity for soils with a high, medium, and low value of C. In these figures, it is evident that the tillage adjustment using estimated C values predicted the trend of a reduction in K_e with increasing rainfall kinetic energy since last tillage; however, this adjustment does not account for most of the variability in the K_{opt} values.

5.3. Adjustments for event size

As the variables associated with event size displayed most correlation to optimized values of K_e, an attempt was made to use these variables to analyze some of the variability that was not explained by the tillage and crusting adjustment. Although few studies have attempted to develop relationships between either event kinetic energy or rainfall amount and the effective hydraulic conductivity, there are several possible explanations for the importance of these factors. Rawls et al. (1991) showed that steady-state infiltration rates on bare soil increased by 42% to 132% as the rainfall intensity increased from 76 to 127 mm h^{-1} under simulated rainfall on a Bearden silty clay loam soil. Other studies have confirmed results such as these; however, few give explanations for the increase in infiltration rates with rainfall intensities or amounts. Beven and Germann (1982) suggest macroporosity as one possible explanation for this phenomenon. Under light rains of low intensity, many larger macropores do not contribute to infiltration as the available water supply is not sufficient to sustain flow in these pores. As intensity or amounts of rain increase, there would be an additional supply of water at the surface and the effects of these macropores would become more evident, resulting in a much greater infiltration rates.

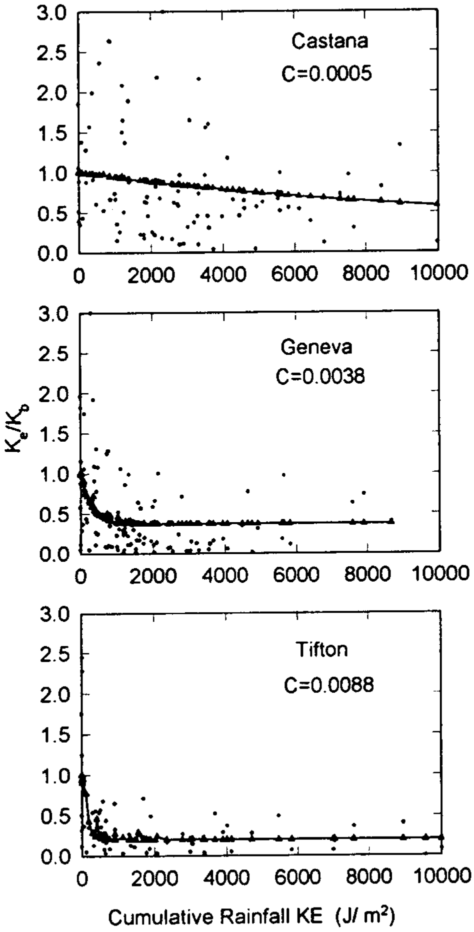

Fig. 1. Comparison of optimized effective conductivities with effective conductivities predicted by the proposed tillage adjustments at three sites. ●, Optimized; △, calculated.

The strong correlation between event size parameters and effective conductivities may also be attributable to deficiencies in the Green–Ampt equation or the WEPP model. If parameters such as depth of ponded water or time to ponding are related to rainfall intensity or amount and this relationship is not accounted for correctly in the model, then optimized values of K_e would display this trend. The longer and more intense events may also violate the assumptions inherit to the Green–Ampt equation. In these events, the wetting front may advance deeper than the depth of the infiltration zone (200 mm) and transient crust conditions during the storm are much more significant. These deficiencies could be corrected through manipulations of the effective conductivity.

The proposed adjustment for event size, the ‘rainfall adjustment’ (*RA*), was developed as another factor to be multiplied with the baseline hydraulic conductivity and the tillage adjustment developed in the previous section. Therefore, the event rainfall, rainfall kinetic energy, and several other variables were regressed with a transformed effective conductivity calculated as

$$RA = \frac{K_e}{K_b \cdot TA} \tag{17}$$

where K_e was optimized effective conductivity for the event, K_b was optimized baseline conductivity (from Table 5), and TA was the tillage adjustment calculated for the given event using Eq. (15). Several different transformations and equation forms were tested using stepwise regression techniques and non-linear curve fitting with a wide variety of variables. The following equation provided the 'best' results in terms of

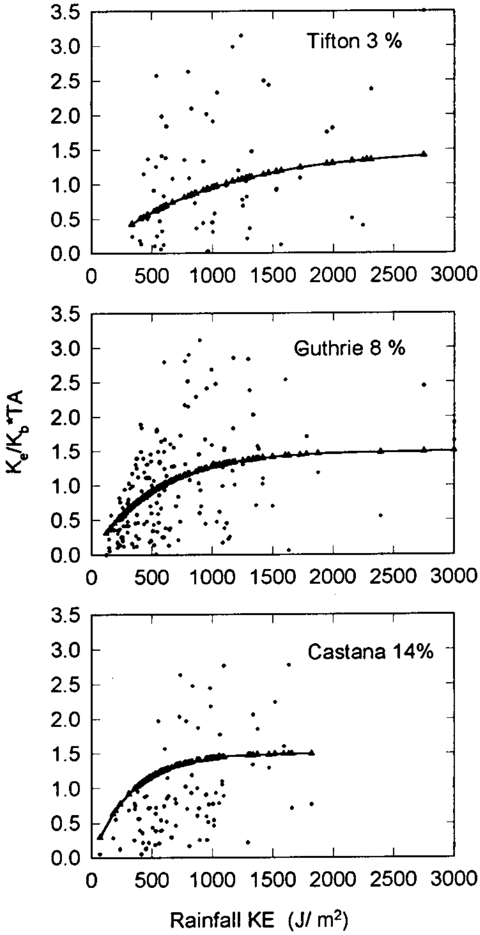

Fig. 2. Comparison of optimized effective conductivities with effective conductivities predicted by the proposed rainfall adjustments at three sites. ●, Optimized; △, calculated.

reduction in error and functionality:

$$RA = 1.5(1 - \mathrm{e}^{-(0.00045+0.0185\mathrm{Slp})\mathrm{rain}KE}) \tag{18}$$

where Slp is per cent slope and rain KE is kinetic energy of the event (in J m^{-2}). Using this equation, the maximum adjustment for rainfall is 1.5. The slope term in the exponential coefficient was determined by regressing various soil and plot characteristics to optimized coefficients determined using SAS non-linear curve-fitting techniques for each of the eleven sites. All of the variables in the WEPP slope and soil input files were included in this analysis; however, slope was the only variable to exhibit a significant correlation. This term indicates that the maximum adjustment is attained more rapidly on plots with steep slopes (see Fig. 2). Conversely, rainfall adjustment has less effect on plots with low slopes. Although prediction of optimized K_e values at most sites was essentially the same if a constant value of 0.0017 was used instead of this slope term, results at Tifton (3% slope) and Castana (14% slope) were dramatically improved when the slope term was incorporated. Because all but three of the plots in this study were on slopes ranging from 5% to 8%, additional data from plots with a wider range of slopes should be used to validate this relationship.

Table 7 shows the improvement obtained using the rainfall adjustment in terms of the model's ability to determine the optimum values of K_e. At most sites the model efficiencies were increased approximately 50%. Average model efficiency increased from 0.14 to 0.23, indicating that the inclusion of the rainfall adjustment significantly improved the prediction of optimized values of K_e. Holly Springs and Castana were the only sites where the rainfall adjustment did not improve the results. Plots of rainfall kinetic energy against rainfall adjustment (Fig. 2 shows three cases) indicated that the trend of higher effective conductivities with increasing values of rainfall

Table 7
Improvement in model efficiencies using the rainfall adjustment

Site	Av. RA	Range RA	Nash–Sutcliffe model efficiency[a]		
			$K_b \cdot TA$	$K_b \cdot TA \cdot RA$	Improvement
Bethany	0.96	0.22–1.49	−0.11	−0.07	0.04
Castana	1.27	0.29–1.49	0.05	0.04	−0.01
Geneva	0.82	0.26–1.48	0.17	0.30	0.13
Guthrie	0.97	0.31–1.50	0.00	0.25	0.25
Holly Springs	0.73	0.20–1.46	0.17	0.15	−0.02
Madison	0.81	0.41–1.39	0.09	0.13	0.04
Morris	0.86	0.33–1.42	0.48	0.65	0.12
Pendleton	0.61	0.20–1.18	0.01	0.12	0.11
Presque Isle	0.73	0.20–1.45	0.22	0.42	0.20
Tifton	0.90	0.42–1.41	0.32	0.40	0.08
Watkinsville	0.95	0.34–1.50	0.13	0.17	0.04
Average	0.87		0.14	0.23	0.09

[a] Model efficiency calculated between predicted K_e and optimized values.

kinetic energy was evident at all of the sites; however, the shape of the function differed from site to site.

5.4. Adjustments for antecedent moisture

The final adjustment investigated was designed to account for antecedent moisture conditions prior to the events. Although correction of curve numbers to account for moisture conditions of the soil is common in many models, hydraulic conductivity in the Green–Ampt equation has never been manipulated to account for these conditions. The suction potential term in the Green–Ampt equation is designed to account for water content of the soil prior to an event. However, as WEPP uses a single-layer approach, where only moisture content in the infiltration zone (upper 200 mm) is considered, this term may not sufficiently account for moisture conditions throughout the soil profile. The fact that the parameters relating to antecedent moisture conditions were more correlated to the optimized K_e values than parameters used in the tillage adjustment indicates that the use of these terms could improve prediction of event K_e values.

The method of developing a relationship to adjust K_e for the antecedent moisture conditions was similar to that for the rainfall adjustment. Rainfall depth of the five days preceding the event (5dam) and soil water content of the soil layer immediately below the infiltration zone ($sw3$) were selected as primary independent variables as they exhibit the highest correlation to K_{opt}. These variables and several transformations and interactions were regressed with transformed optimized effective conductivities in the form of

$$\text{AMA} = \frac{K_e}{K_b \cdot TA \cdot RA} \tag{19}$$

where AMA is the moisture adjustment and the remainder of the terms were previously defined. As the amount of water in the third soil layer was highly dependent on layer thickness, a relative measure of saturation was required. The variable with the highest correlation to values of AMA was soil water in the third layer divided by the amount of soil water that this layer could hold at field capacity. Although rainfall amount in the preceding 5 days did display a higher correlation at four sites, the relationship between 5 day rainfall totals and AMA was not as consistent from site to site. The relationship that produced the best results over all sites was

$$\text{AMA} = 1.30\left(\frac{sw3}{fc3}\right)^{-2.5} \tag{20}$$

where $sw3$ is soil water in the layer beneath the infiltration zone and $fc3$ is the amount of water that this layer could hold at field capacity. Not only did this equation provide the best fit to calculated values of AMA, but it seems intuitively sound as well. In the field, one would expect more runoff from a soil saturated to 250 mm than if it was at field capacity, given both conditions have equivalent moisture at 100 mm. Whereas the moisture content of the upper 200 mm is probably sufficient for smaller events, for larger events, where conditions below 200 mm may be important, WEPP has no method for modifying the amount of predicted runoff. By reducing effective conductivity, this equation allows the model to predict more runoff under these conditions.

The values calculated for AMA generally ranged from 0.25 to 1.25, with an average of 0.86 (Table 8). Although this range may seem large, the standard deviations of the means indicate that on several sites (Pendleton, Madison, and Geneva) AMA did not vary much, whereas at other sites there is significant variation (Tifton, Morris, and Castana). This can be explained by both distribution of rainfall at the sites and by differences in the soil properties of the sub-layers. Use of the moisture adjustment increased the average model efficiency of predicting effective conductivities over using just the tillage adjustment (+0.10) or the tillage and rainfall adjustment (+0.02). Although this may not seem like a significant increase, the adjustment tended to improve predicted values of K_e more for the events where soil water in the third layer was high than it did under average conditions (Fig. 3). As runoff under extremely wet conditions is generally associated with larger events, by reducing K_e for these events, the adjustment could offer significant improvements in the prediction of runoff. It is also apparent from Fig. 3 that the moisture adjustment tends to perform poorly at conditions near field capacity. This may be a result of the WEPP model structure, as the water balance component of WEPP only allows the moisuture above field capacity to move down through the soil profile. Therefore, in the absence of plant uptake, the water content will not drop below field capacity. This, however, should have little effect on runoff, as AMA is usually much closer to one under these conditions.

Table 8
Improvement in model efficiencies using the moisture adjustment

Site	Calculated		Nash–Sutcliffe model efficiency[a]		
	Av. AMA[b]	Range AMA	$K_b \cdot TA$	$K_b \cdot TA \cdot RA \cdot \mathrm{AMA}$	Improvement
Bethany	0.84 ± 0.12	0.54–1.17	−0.11	−0.05	0.06
Castana	0.93 ± 0.22	0.26–1.23	0.05	0.13	0.08
Geneva	0.77 ± 0.09	0.46–0.99	0.17	0.22	0.05
Guthrie	0.86 ± 0.19	0.35–1.25	0.00	0.30	0.30
Holly Springs	0.87 ± 0.15	0.56–1.21	0.17	0.18	0.01
Madison	1.05 ± 0.08	0.91–1.19	0.09	0.22	0.13
Morris	0.90 ± 0.22	0.43–1.24	0.48	0.59	0.11
Pendleton	0.79 ± 0.03	0.75–0.86	0.01	0.01	0.00
Presque Isle	0.90 ± 0.20	0.27–1.21	0.22	0.41	0.19
Tifton	0.78 ± 0.23	0.24–1.25	0.32	0.55	0.23
Watkinsville	0.76 ± 0.12	0.47–1.01	0.13	0.12	−0.01
Average	0.86		0.14	0.24	0.10

[a] Model efficiency calculated between predicted K_e and optimized values.

[b] Average calculated value of MA ±1 SD.

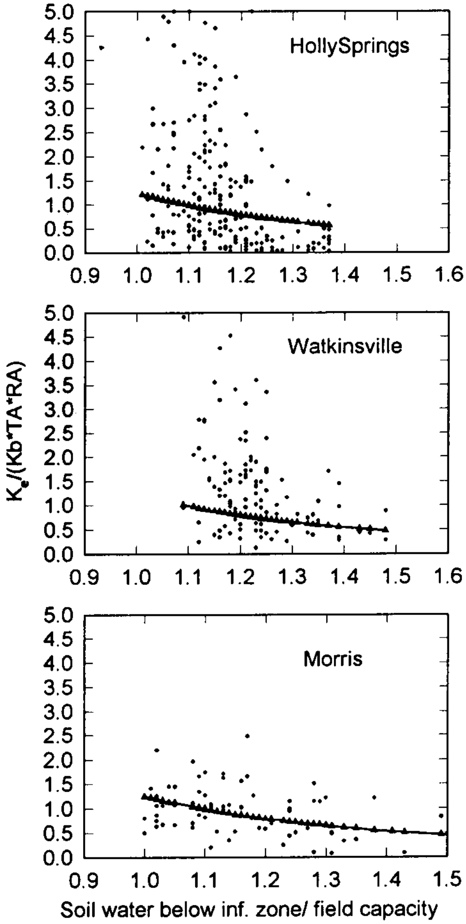

Fig. 3. Comparison of optimized effective conductivities with effective conductivities predicted by the proposed adjustment for moisture content. ●, Optimized; △, calculated.

5.5. Comparison of adjustments using WEPP predicted runoff

To compare the effects of using these adjustments on predicted runoff amounts, each adjustment was incorporated into WEPP. A total of four WEPP versions were tested: (1) a constant K_e version in which no temporal variation was allowed (kec); (2) a version with just the tillage adjustment (kbta); (3) a version with the tillage adjustment and the rainfall adjustment (kbtra); (4) a version with the tillage, rainfall, and moisture adjustments (kbtrma). As using any single value of hydraulic conductivity for all methods would produce a bias towards an individual method, K_b was calibrated for each of the versions. This calibrated value of K_b was inserted into the WEPP soils files and each version was run and the output was analyzed.

The optimized baseline conductivities and model efficiencies of each version are given in Table 9. Baseline values of hydraulic conductivity were all higher than effective conductivities obtained for the constant-value version. This was expected, as constant values represent the average effective conditions rather than the freshly tilled conditions. Using the tillage adjustment alone, the average effective value, K_e, was approximately 42% of K_b. Effects of the rainfall and moisture adjustments on the calibrated values of K_b were minimal compared with effects of the tillage adjustment, 49% and 43%, respectively. Generally, optimized values of K_b using the rainfall adjustments were lower than those obtained using the tillage adjustment alone. The addition of the moisture adjustment raised the optimized value closer to that obtained using the tillage adjustment. Although both the rainfall and moisture adjustments were developed so that the net effect on K_b would be minimal (i.e. equations were fitted using the K_b of the tillage adjustment), it does appear that these adjustments had some effect on the optimized baseline values.

The average model efficiency was highest for the version of the model that used all of the adjustments, and this version performed best at nine of the 11 sites. All of the versions that included temporal adjustments performed much better than the constant-value version. Inclusion of the tillage adjustment produced the greatest effect on average model efficiency (+0.09), and the remaining adjustments displayed smaller gains (+0.04 and +0.01 for the inclusion of the rainfall and moisture adjustments, respectively). Although model efficiency was a good tool for

Table 9
Comparison of optimized baseline conductivities and model efficiencies for WEPP using four temporal variation methods

Site	Version[a]							
	Kec		Kbta		Kbtra		Kbtrma	
	Opt. K_b	*ME*[b]	Opt. K_b	*ME*	Opt. K_b	*ME*	Opt. K_b	*ME*
Bethany	1.22	0.81	3.65	0.82	2.97	0.82	3.49	0.84
Castana	2.04	0.46	2.38	0.49	1.73	0.53	1.70	0.54
Geneva	2.27	0.63	5.14	0.72	4.26	0.74	4.60	0.76
Guthrie	6.19	0.85	16.73	0.85	13.07	0.87	15.27	0.89
Holly Springs	0.31	0.84	0.72	0.87	0.70	0.86	0.73	0.87
Madison	1.80	0.74	2.01	0.77	1.94	0.75	1.87	0.78
Morris	7.68	0.40	16.41	0.59	12.90	0.69	13.29	0.71
Pendleton	0.51	0.07	1.76	0.07	1.74	0.23	1.79	0.22
Presque Isle	2.38	0.19	3.82	0.46	3.19	0.55	3.82	0.53
Tifton	7.87	0.49	18.14	0.66	15.47	0.71	17.80	0.73
Watkinsville	4.41	0.84	19.15	0.84	15.51	0.86	20.12	0.87
Average	1.00[c]	0.56	2.40[c]	0.65	2.04[c]	0.69	2.30[c]	0.70

[a] Kec: constant K_e; Kbta: K_e varies with tillage adjustment; Kbtra: K_e varies with tillage and rainfall adjustment; Kbtrma: K_e varies with tillage, rainfall, and moisture adjustment.

[b] Model efficiency calculated between WEPP predicted runoff and measured values.

[c] This is average ratio of K_b/K_{ec}.

K_b in mm h^{-1}.

Table 10
Comparison of regression statistics for WEPP using four methods of temporal variation

Site	Version[a]											
	Kec			Kbta			Kbtra			Kbtrma		
	Slp	Int	r^2 [b]	Slp	Int	r^2	Slp	Int	r^2	Slp	Int	r^2
Bethany	0.90	0.02	0.81	0.91	0.81	0.82	0.85	2.33	0.83	0.86	2.02	0.84
Castana	0.82	0.50	0.59	0.84	0.05	0.62	0.80	0.76	0.62	0.89	0.18	0.65
Geneva	0.83	0.67	0.67	0.80	0.32	0.74	0.73	1.83	0.74	0.73	1.81	0.76
Guthrie	0.97	−0.99	0.87	0.97	−1.04	0.87	0.90	0.63	0.87	0.94	−0.02	0.89
Holly Springs	0.87	1.39	0.84	0.85	1.82	0.87	0.79	3.57	0.87	0.80	3.49	0.88
Madison	0.69	1.57	0.75	0.71	1.42	0.78	0.63	2.75	0.78	0.65	2.40	0.81
Morris	0.69	0.05	0.52	0.74	−0.29	0.66	0.72	0.77	0.70	0.78	0.48	0.73
Pendleton	0.61	−0.18	0.41	0.67	−0.12	0.41	0.64	0.37	0.42	0.65	0.43	0.41
Presque Isle	0.55	1.12	0.36	0.63	0.68	0.53	0.59	1.90	0.56	0.63	1.37	0.56
Tifton	0.79	0.77	0.59	0.85	2.19	0.69	0.78	3.60	0.71	0.84	2.59	0.74
Watkinsville	0.97	−0.81	0.86	1.01	−1.13	0.87	0.92	0.92	0.86	0.96	0.31	0.88
Average	0.79	0.37	0.66	0.82	0.43	0.71	0.76	1.77	0.72	0.79	1.37	0.74

[a] Kec: constant K_e; Kbta: K_e varies with tillage adjustment; Kbtra: K_e varies with tillage and rainfall adjustment; Kbtrma: K_e varies with tillage, rainfall, and moisture adjustment.

[b] Regression statistics calculated between WEPP predicted runoff and measured values; predicted runoff = Slp · measured runoff + Int.

determining overall goodness of fit for model results, regression analysis and graphical comparisons were also used to provide more insight concerning these results. The correlation coefficients, r^2, were generally close to the model efficiencies and indicated the same trends (Table 10). The slope and intercept of the regression line between measured and predicted values can be used as a measure of bias (Flavelle, 1992). Results from a perfect model would have a slope of one and an intercept of zero. For every version of the model and almost every site, the slopes were less than one and the intercepts were greater than zero. This indicates that all versions over-predicted runoff for smaller events and under-predicted runoff for larger events. Of the various WEPP versions, the version with the tillage adjustment alone appeared to be the least biased, as it had the highest slope and lowest intercept. Although there was little difference between the slope terms for any of the versions (range of 0.76–0.82), the intercepts were considerably different, ranging from 0.37 for Kbta to 1.77 for Kbtrma. This indicates that the rainfall adjustment made the bias more pronounced.

6. Conclusions

Optimized event values of Green–Ampt effective hydraulic conductivities were determined using a computer database of natural runoff plot data consisting of over 220 plot-years from 11 sites. These data were used to investigate the temporal variability in effective hydraulic conductivity. Parameters that were significantly correlated to event hydraulic conductivities fell into three distinct groups: those associated with event size, those associated with antecedent moisture conditions, and those related to time since tillage. An equation for adjusting hydraulic conductivity to account for crusting was derived. This equation used an exponential decay function based on cumulative rainfall kinetic energy since last tillage to describe the decrease in conductivity with time since tillage. Equations describing adjustments to account for event size and antecedent moisture conditions were also derived based on the optimized data. These equations used rainfall kinetic energy and the ratio of the water content over the field capacity of the sub-infiltration zone to account for changes in effective hydraulic conductivity. Each adjustment was incorporated into the WEPP model, and runoff predictions were compared with the measured data. The tillage adjustment improved the overall average model efficiency from 0.56 to 0.65 when optimized baseline values of hydraulic conductivity were used. The adjustments for rainfall and antecedent moisture also improved the model efficiency, although they also increased the bias of under-predicting runoff of the larger events. As they may be a result of the WEPP model structure, it is suggested that further testing and validation be conducted to assess the reliability of these adjustments. Furthermore, these results are empirical in nature and may not be applicable to conditions outside the realm of this database or for models that implement the Green–Ampt equations in a different manner from WEPP.

References

Beven, K.J. and Germann, P., 1982. Macropores and water flow in soils. Water Resour. Res., 18(5): 1311–1325.

Bosch, D.D. and Onstad, C.A., 1988. Surface seal hydraulic conductivity as affected by rainfall. Trans. ASAE, 31(4): 1120–1127.

Bradford, J.M. and Huang, C., 1993. Mechanisms of crust formation: physical components. In: M.E. Sumner and B.A. Stewart (Editors), Advances in Soil Science, Soil Crusting Chemical and Physical Processes. Lewis, Chelsea, IL, pp. 55–72.

Brakensiek, D.L. and Rawls, W.J., 1983. Agricultural management effects on soil water processes Part II: Green and Ampt parameters for crusting soils. Trans. ASAE, 26(6): 1753–1759.

Chu, S.T., 1978. Infiltration during an unsteady rain. Water Resour. Res., 14(3): 461–466.

Eigel, J.D. and Moore, I.D., 1983. Effect of rainfall energy on infiltration into a bare soil. In: Proceedings of ASAE Conference on Advances in Infiltration, Chicago, IL. ASAE, St. Joseph, MI, pp. 188–199.

Flavelle, P., 1992. A quantitative measure of model validation and its potential use for regulatory purposes. Adv. Water Resour., 15: 5–13.

Green, W.H. and Ampt, G.A., 1911. Studies on soil physics: 1. Flow of air and water through soils. J. Agric. Sci., 4: 1–24.

Lane, L.J. and Nearing, M.A. (Editors), 1989. USDA—Water Erosion Prediction Project: Hillslope Profile Model Documentation. NSERL Rep. 2, USDA-ARS, West Lafayette, IN.

Nash, J.E. and Sutcliffe, J.E., 1970. River flow forecasting through conceptual models, Part 1—A discussion of principles. J. Hydrol., 10(3): 282–290.

Nearing, M.A., Foster, G.R., Lane, L.J. and Finkner, S.C., 1989. A process based soil erosion model for USDA water erosion prediction project. Trans. ASAE, 32(5): 1587–1593.

Nearing, M.A., Deer-Ascough, L. and Laflen, J.M., 1990. Sensitivity analysis of the WEPP hillslope profile erosion model. Trans. ASAE, 33(3): 839–849.

Nearing, M.A., Liu, B.Y., Risse, L.M. and Zhang, X., 1995. The relationship between curve numbers and Green and Ampt effective hydraulic conductivities for use in the WEPP model. Trans. ASAE, submitted.

Rawls, W.J. and Brakensiek, D.L., 1983. A procedure to predict Green and Ampt infiltration parameters. In: Proceedings of ASAE Conference on Advances in Infiltration, Chicago, IL. ASAE, St. Joseph, MI, pp. 102–112.

Rawls, W.J., Brakensiek, D.L., Simanton, J.R. and Kohl, K.D., 1990. Development of a crust factor for the Green Ampt model. Trans. ASAE, 33(4): 1224–1228.

Rawls, W.J., Onstad, C.A. and Brakensiek, D.L., 1991. Temporal variability of infiltration for agricultural systems. ASAE Pap., 91-2547.

Risse, L.M., 1994. Validation of WEPP using natural runoff plot data. Ph.D. Dissertation, National Soil Erosion Research Laboratory, Purdue University, West Lafayette, IN, 230 pp.

Risse, L.M., Nearing, M.A. and Savabi, R., 1992. An evaluation of hydraulic conductivity prediction routines for WEPP using natural runoff plot data. ASAE Pap., 92-2142.

Risse, L.M., Nearing, M.A. and Savabi, M.R., 1994. Determining the Green–Ampt effective hydraulic conductivity from natural runoff plot data for the WEPP model. Trans. ASAE, 37(2): 411–418.

Sharpley, A.N. and Williams, J.R. (Editors), 1990. EPIC—Erosion/Productivity Impact Calculator: 1. Model documentation. US Dep. Agric. Tech. Bull. 1768.

Skaggs, R.W. and Khaleel, R., 1982. Infiltration. In: C.T. Haan, H.P. Johnson and D.L. Brakensiek (Editors), Hydrologic Modeling of Small Watersheds. Monograph 5, American Society of Agricultural Engineers, St. Joseph, MI, pp. 121–166.

Van der Sweep, R.A., 1992. Evaluation of the Water Erosion Prediction Project's watershed version hydrologic component on a semi-arid rangeland watershed. M.S. Thesis, University of Arizona, Tucson, AZ.

Van Doren, D.M. and Allmaras, R.R., 1978. Effect of residue management practices on the soil physical environment, micro climate, and plant growth. Am. Soc. Agron. Spec. Publ. 31. Crop Residue Systems. ASA, CSSA, SSSA, Madison, WI, pp. 49–83.

Zhang, X.C., Nearing, M.A. and Risse, L.M., 1995. Green–Ampt effective hydraulic conductivity under cropped conditions. Trans. ASAE, submitted.