# DETERMINING THE GREEN-AMPT EFFECTIVE HYDRAULIC CONDUCTIVITY FROM RAINFALL-RUNOFF DATA FOR THE WEPP MODEL

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**ABSTRACT.** *The Green-Ampt infiltration equation is used in many different hydrologic models. The effective hydraulic conductivity parameter ($K_e$) within this equation is needed to obtain reliable estimates of infiltration and runoff. In this study, a method was developed for calibrating $K_e$ for the Green-Ampt equation as integrated with the WEPP continuous simulation model using a series of rainfall-runoff events on natural runoff plots. Optimum values of $K_e$ were obtained at seven locations, and the average Nash-Sutcliffe model efficiency for the Green-Ampt/WEPP predictions of runoff on an event basis was 0.46 using these $K_e$ values. Green-Ampt/WEPP tended to overpredict runoff on the small events and underpredict runoff on the larger events. This bias could not be corrected through calibration and indicates a structural flaw in the Green-Ampt equation, the WEPP model, or the available data. Other estimates of effective hydraulic conductivity were obtained from five different parameter estimation methods based on relationships involving common soil properties and were used in the Green-Ampt/WEPP model to predict runoff at each of the locations. None of these methods of estimating the effective hydraulic conductivity consistently outperformed the others for all the data sets. The average Nash-Sutcliffe model efficiency obtained using the best estimated parameters was −0.16, indicating that considerable improvement was obtained with calibration.*

***Keywords.*** *Hydraulic conductivity, Green and Ampt equation, WEPP, Calibration, Hydrologic modeling, Model optimization.*

The Green and Ampt (1911) equation is one of the most widely used equations for modeling one-dimensional vertical flow of water into soil. It was developed from an integration of Darcy's law by assuming infiltration from a ponded surface into a deep, homogeneous soil of uniform antecedent water content. Due to its simplicity and versatility, it has received widespread use and many scientists have modified it for specific applications (Mein and Larson, 1973; Chu, 1978). Additionally, many hydrologic models such as CREAMS (USDA, 1980) and DRAINMOD (Skaggs, 1978) use some form of this infiltration equation.

In 1985, the Water Erosion Prediction Project (WEPP) was initiated to develop improved erosion prediction technology based on modern hydrologic and erosion science that would be process oriented and conceptually a significant improvement over existing technology (Foster and Lane, 1987). WEPP is a continuous simulation computer model which uses the Green-Ampt equation to calculate infiltration and runoff. It contains hydrologic routing, water balance, plant growth, residue decomposition, and soil consolidation models as well as a climate generator and many other components (Lane and Nearing, 1989). Infiltration in WEPP is calculated using a solution of the Green-Ampt-Mein-Larson equation for unsteady rainfall developed by Chu (1978). It is essentially a two-stage process under unsteady rainfall. Initially, the infiltration rate is equal to the rainfall application rate. After ponding, the infiltration rate begins to decrease until the rate approaches a constant value or "final infiltration rate". The infiltration rate for each time increment is calculated by:

$$f = K_e\left(1 + \frac{N_s}{F}\right) \qquad (1)$$

where

$f$ = infiltration rate (L/T)
$N_s$ = effective matric potential (L)
$F$ = cumulative infiltration (L)
$K_e$ = effective hydraulic conductivity (L/T)

In this equation, F is obtained using the Newton-Raphson method to solve:

$$K_e t = F - N_s \ln\left(1 + \frac{F}{N_s}\right) \qquad (2)$$

where t is the time (T).

In equation 1 the effective matric potential, $N_s$, is computed using:

$$N_s = (\phi_e - \Theta_i)\Psi \qquad (3)$$

where

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$\phi_e$ = effective porosity (L/L)
$\Theta_i$ = initial soil water content (L/L)
$\Psi$ = average capillary potential across the wetting front (L)

Therefore, the parameters needed to drive the infiltration component of the model are the effective porosity which is computed on a daily basis from the bulk density, the capillary potential across the wetting front which is computed based on soil properties using an equation developed by Rawls and Brakensiek (1983), the initial water content which is obtained from the WEPP moisture balance component, and the hydraulic conductivity.

Sensitivity analysis on the Green-Ampt equation parameters have indicated that infiltration and runoff amounts were most sensitive to porosity and hydraulic conductivity and less sensitive to $\Psi$ (Skaggs and Khaleel, 1982). An investigation conducted as part of this project to determine if the optimization of $\Psi$ could significantly improve the model results indicated that calibration of $\Psi$ in addition to $K_e$ did not improve the model results. Therefore, the use of the Rawls and Brakensiek (1983) equation for determining $\Psi$ was assumed to be adequate. Since the porosity and water content terms are calculated on a daily basis within WEPP, the only remaining parameter in the Green-Ampt infiltration model that has a significant impact on the runoff predictions is the hydraulic conductivity. Since an ideal test of the Green-Ampt equation would use measured parameters for the porosity and water content, we will use the term G&A/WEPP to signify that we are using values calculated by WEPP in the Green-Ampt equation.

In WEPP, the baseline value of the hydraulic conductivity, $K_e$, for each soil layer is read from the soil input file. Theoretically, this value is intended to represent the effective hydraulic conductivity of the given soil layer. In earlier versions of WEPP, this value of $K_e$ was adjusted daily to account for the effects of climate, tillage, residue, crusting, and macroporosity, however, these adjustments were removed from the version (V93.1) which was used for this study. The value of $K_e$ entered in the soil input file was used as the effective conductivity for each of the storms within the entire simulation and remained constant.

Previous validation studies of the WEPP hydrology component (Van der Zweep and Stone, 1991; Savabi et al., 1990; Kramer and Alberts, 1992) indicated that the model can perform much better if certain parameters are calibrated rather than estimated based on other properties. Nearing et al. (1990), Chaves and Nearing (1991), and Tiscareno-Lopez et al. (1992) have conducted sensitivity analysis on many of the parameters used in the model. Their results generally agree that the rainfall parameters (amount, duration, and intensity) and the parameters which affect infiltration (surface cover and hydraulic conductivity) have the most impact on the runoff predictions. Van der Zweep and Stone (1991) compared the effects of using estimated $K_e$ values to calibrated $K_e$ values on a rangeland watershed and showed the Nash-Sutcliffe model efficiency improved from −0.99 to 0.62 if calibrated values of $K_e$ were used. In another study, Risse et al. (1992) compared six methods of calculating estimates for $K_e$ and two methods of calibrating it to predict runoff for natural runoff plots at six locations using a series of single storm simulations in WEPP. The best results were obtained using calibrated values of $K_e$, with a Nash-Sutcliffe model efficiency of 0.54. Without calibration, the best method of estimating the saturated hydraulic conductivity was the method developed for WEPP and given in Lane and Nearing (1989). It had a model efficiency of 0.27. These results indicate that current hydraulic conductivity estimation methods are inadequate, and the model must be calibrated to measured data unless better estimation routines can be developed.

### OBJECTIVE

The objective of this study was to derive and evaluate parameters for the Green-Ampt equation in WEPP using a variety of methods and to determine which method, if any, is likely to be most suitable for estimating effective hydraulic conductivity values for use in WEPP. Additionally, the results obtained using calibrated parameters were compared to the measured data to assess the accuracy of the G&A/WEPP runoff predictions and locate potential sources of error.

## MATERIALS AND METHODS

### DATABASE AND MODEL INPUTS

Thousands of plot years of natural runoff data were obtained from the National Erosion Laboratory at Purdue University. This included most of the natural runoff plot data used to develop the USLE as well as additional data from more current natural runoff plots. Sixteen plots at seven locations were chosen for use in this study (table 1). These sites were selected based on the quality of the data and to obtain a scattered distribution of soil types and geographical locations. All of the selected plots were in continuous cultivated fallow conditions to minimize the effects of plant growth and residue on infiltration.

Once the sites were selected, the data were formatted for use with WEPP version 93.1 in the continuous simulation mode. Climate, soil, management, and topographic files were constructed based on the recorded data for each of the sites. At each site, there were one or more replicates under identical conditions. Since each replicate used the same input files, the model would produce the same estimate of runoff for each replicated plot. Therefore, the measured values were averaged resulting in one value of average measured runoff rather than calibrating to the individual plots.

The measured climate data usually consisted of maximum and minimum temperatures and daily rainfall amounts. In addition to this, detailed breakpoint data were

**Table 1. Sites and plots selected for WEPP validation and optiminization**

| Site | Soil | Years | Slope (%) | R* |
|---|---|---|---|---|
| Holly Springs, Miss. | Providence sil | 1961-68 | 5.0 | 2 |
| Madison, S.D. | Egan sicl | 1961-70 | 5.8 | 2 |
| Castana, Iowa | Monona sil | 1960-71 | 14.0 | 2 |
| Pendleton, Oreg. | Thatuna sil | 1979-89 | 16.0 | 2 |
| Presque Isle, Maine | Caribou grl | 1961-69 | 8.0 | 3 |
| Morris, Minn. | Barnes l | 1961-71 | 5.9 | 3 |
| Tifton, Ga. | Tifton sl | 1959-66 | 3.0 | 2 |

* Replicates.

available for most of the storms which produced runoff. Since previous studies had determined that the model was sensitive to the rainfall parameters (rainfall duration, time to peak, and peak intensity), these parameters were calculated using the breakpoint data if available. The remainder of the climate parameters were generated using CLIGEN version 2.3, the stochastic weather generator included with WEPP. These generated parameters included solar radiation, wind velocity and direction, and dew point temperature. They should not have a significant impact on the predicted runoff under fallow conditions.

The WEPP model allows for nonuniform slopes; however, all of the slopes in this study were of near uniform slope with constant widths that could be represented with a single overland flow element. The inputs required in the topographic file consisted of the slope width, length, aspect, and a single pair of distance/slope measurements. All of the plots were of standard natural runoff plot dimensions (4.05 × 22.13 m) except for those at Tifton (8.10 × 44.26 m) and Pendleton (4.05 × 33.50 m), and were on slopes given in table 1.

The WEPP cropland management files supply the information required for the plant growth, residue decay, management practices, tillage, and initial conditions. Although much of this data was available, some assumptions were required. The initial conditions were estimated by running continuous simulations of 10 years using assumed initial conditions and then averaging the values on January 1 of the second through the tenth years to determine an average initial condition for the parameters in question. Information on the dates and types of tillage were given in the data. The tillage database included in WEPP documentation was used to obtain tillage parameters including the depth, surface roughness after tillage, tillage intensity, ridge height, and ridge spacing.

The soil profile input file for WEPP may have up to 10 soil layers. The first line of the file contains general information about the soil including the soil name and texture, the albedo, initial saturation, and three erodibility parameters. The remainder of the input soils file contains information on each of the soil layers. Each of these layers required the following inputs: thickness of layer, consolidated bulk density, hydraulic conductivity, the water content at field capacity and wilting point, percent sand and clay, percent organic matter, CEC, and percent rock fragments. All of these inputs except for $K_e$ and initial saturation were obtained by using information that could be found in the original data sheets, experiment station bulletins, SCS pedon descriptions, and data in the WEPP soils compendium. The initial saturation was assumed based on the average results from preliminary 10-year continuous simulations. Table 2 gives a description of the soil properties for the upper soil layer at each of the sites.

Measured values of hydraulic conductivity were taken from the literature (table 3). Five of the soils in this study were part of the WEPP cropland soil field erodibility experiments (Elliot et al., 1989). The hydraulic conductivities on these soils was measured under simulated rainfall (average intensity of 62 mm/h) in 0.50 m × 0.75 m plots on a bare, freshly tilled soil. The values reported in the table are the average of eight replicates. Two other values of hydraulic conductivity were measured using a constant head permeameter on soil cores as described in Onstad et al., 1984. These values represent the average of six replicates.

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

| Soil | Texture Class | Bulk Density (Mg/m³) | Field Capacity (mm/mm) | Sand (%) | Clay (%) | Organic Matter (%) | CEC (cmol/kg) |
|---|---|---|---|---|---|---|---|
| Providence | sil | 1.34 | 0.240 | 2.0 | 19.8 | 0.81 | 9.3 |
| Egan | sicl | 1.21 | 0.450 | 7.0 | 32.2 | 3.70 | 25.1 |
| Monona | sil | 1.30 | 0.260 | 7.1 | 23.5 | 2.00 | 20.1 |
| Thatuna | sil | 1.32 | 0.375 | 28.0 | 23.0 | 4.30 | 16.2 |
| Caribou | grsil | 1.49 | 0.247 | 38.8 | 13.7 | 3.76 | 13.2 |
| Barnes | l | 1.30 | 0.260 | 39.4 | 23.2 | 3.37 | 18.4 |
| Tifton | ls | 1.72 | 0.075 | 87.0 | 5.7 | 0.70 | 4.1 |

## OPTIMIZATION ALGORITHM

The process of calibrating a model parameter generally consists of two steps: definition of an objective function and development of a search algorithm. The choice of an objective function is often subjective, yet it is important and should adequately reflect the intended hydrologic characteristic. The objective function used here was the least squares error (LSE) criterion as applied to observed and predicted runoff volumes from selected events. It is defined as:

$$LSE = \sum_{t=1}^{n} (O_t - Y_t)^2 \qquad (4)$$

where $Y_t$ and $O_t$ are the observed and predicted runoff volumes for event t, and n is the number of events. The minimizing of this objective function for parameter estimation implies certain assumptions about the statistical distribution of the residuals. These assumptions were given by Clarke (1973) as first, the residuals must have zero mean and constant variance ($\sigma^2$); and second, that the residuals must be mutually uncorrelated. If these assumptions are not met, estimates of model parameters may still be obtained by minimizing the function, but their interpretation may be erroneous. The most important

**Table 3. Calculated hydraulic conductivities for each method of estimation**

| | Hydraulic Conductivity (mm/h) for Each Method of Estimation* | | | | | | |
|---|---|---|---|---|---|---|---|
| Soil | MEAS | OPT | RAEQ | TABLE | TRI | EPIC | RSEQ |
| Providence | 3.4 | 0.31 | 0.70 | 6.8 | 1.6 | 8.53 | 1.26 |
| Egan | 19.1† | 1.73 | 0.23 | 1.5 | 0.8 | 4.34 | 9.87 |
| Monona | 3.1 | 2.04 | 0.28 | 6.8 | 1.5 | 7.32 | 5.94 |
| Thatuna | NA | 0.70 | 1.62 | 6.8 | 4.0 | 7.49 | 15.87 |
| Caribou | 8.1 | 2.32 | 0.88 | 13.2 | 10.0 | 10.15 | 17.65 |
| Barnes | 19.1<br>42.0† | 9.53 | 2.88 | 13.2 | 5.0 | 7.42 | 15.14 |
| Tifton | 14.9 | 7.87 | 25.10 | 61.1 | 190.0 | 11.48 | 16.43 |

* MEAS – measured under simulated rainfall (from Elliot et al., 1989).
OPT – calibrated value.
RAEQ – calculated using equation 5.
TABLE – from table 4 of Rawls and Brakensiek (1982).
TRI – from figure 1.
EPIC – calculated using equation 7.
RSEQ – calculated using equation 8.

† These values measured using constant head permeameter on soil cores (from Onstad et al., 1984).

advantage of the least-squares method is its ability to produce stable reduced data in the presence of errors (McCuen and Synder, 1986).

The effects of using absolute differences in total runoff and LSE weighted by the total runoff volume as the objective functions were compared using WEPP single storm simulations. Generally, the use of absolute differences as the objective function tended to overemphasize numerous small events while the weighted approach overemphasized the larger events. While the use of absolute errors resulted in a better match between the measured and predicted values of total runoff, the LSE tended to place more emphasis on the outliers usually associated with the larger events. Since these events generally cause more runoff and soil loss than the many smaller events, the LSE would give a value of effective conductivity which may be more appropriate for these larger events. An event-based optimization was chosen over an annual or average annual basis because: (1) the data were not collected for the entire year at many of the locations, and (2) the effects of winter conditions and gaps in the measured data could be avoided by using specified events rather than the total runoff for the year.

In order to automate the calibration procedure, all of the selected events and their corresponding values of runoff were recorded in an "events" file. As many events as possible were included in this file, however, some measured events were excluded. To prevent any bias in the data set, all events for which WEPP predicted significant runoff (over 3 mm) were included in the events file even if there were no measured values. Criteria for exclusion of events were:

- Gross differences in runoff produced on replicated plots which seemed to indicate a measurement error.
- No breakpoint rainfall data were available to calculate the disaggregated rainfall parameters.
- Measured runoff was less than 1 mm (WEPP threshold for output) and WEPP predicted no runoff.
- The entire period of rainfall and subsequent runoff and soil loss had occurred over several days or many storms contributed to a single measurement of runoff and soil loss.
- The storm occurred during a period where there was snow on the ground or the soil or air temperature was below freezing during the event.

Once an objective function is selected, one must select a scheme for minimization. This is commonly achieved by methods not requiring the evaluation of derivatives (gradient methods) due to the complexity of these methods and most hydrologic models. Instead, direct search methods are usually employed. The optimization technique selected for determining the hydraulic conductivity was based on the golden section algorithm (Himmelblau, 1972). This is a one-dimensional search technique in which one must specify the interval in which the minimum lies for a unimodal function. This interval will then be reduced using a sequential search technique based upon splitting the line into two segments until the interval is reduced to a user-specified fraction of the original interval. The advantage which the golden section offers over other search algorithms is that by breaking the interval into two segments where the ratio of the larger segment to the entire interval is the same as the ratio of the smaller segment to the larger one is that the reduction of the interval is usually accomplished in the minimum number of steps.

## $K_e$ ESTIMATION METHODS

In addition to determining the calibrated values of $K_e$, several methods of estimating the effective hydraulic conductivity based on soil properties were explored. While most of these methods were designed to estimate values of the saturated hydraulic conductivity, in this study they will be compared to the calibrated Green-Ampt effective hydraulic conductivities in the WEPP model (OPT values of $K_e$).

The first method, "RAEQ", is based on an equation developed by Rawls et al. (1989) which computes an estimate of the hydraulic conductivity, $K_{sat}$ using the following equations:

$$K_{sat} = \frac{\phi_e^3}{(1-\phi_t F_a)^2 \left(\frac{0.001\rho}{\theta_r}\right)^2 0.00020\,C^2} \qquad (5)$$

where

$\phi_e$ and $\phi_t$ = effective and total porosities (L/L)
$\theta_r$ = residual soil water content (L/L)
$F_a$ = entrapped air correction factor
$\rho$ = soil bulk density ($M/L^3$)

The parameter C is predicted from:

$$\begin{aligned} C = &-0.17+18.1\,Cl-69.0\,Sa^2Cl^2-41.0\,Sa^2Si^2 \\ &+1.18\,Sa^2\left(\frac{\rho}{1000}\right)^2+6.9\,Cl^2\left(\frac{\rho}{1000}\right)^2 \\ &+49.0\,Sa^2Cl-85.0\,SiCl^2 \end{aligned} \qquad (6)$$

where Sa, Si, and Cl are fractions of sand, silt, and clay.

The "TABLE" method simply uses table 4 of Rawls and Brakensiek (1982) which estimates the saturated hydraulic conductivity based on the textural class of the soil. The

**Table 4. Green-Ampt/WEPP model efficiencies for runoff predictions using hydraulic conductivities from various methods of estimation**

| | Model Efficiency for Each Method of Estimation* | | | | | |
|---|---|---|---|---|---|---|
| Soil | OPT | RAEQ | TABLE | TRI | EPIC | RSEQ |
| Providence | 0.84 | 0.79 | –0.25 | 0.59 | –0.40 | 0.66 |
| Egan | 0.74 | 0.24 | 0.74 | 0.65 | 0.56 | 0.12 |
| Monona | 0.46 | –1.75 | –0.89 | 0.38 | –1.01 | –0.65 |
| Thatuna | 0.07 | –0.75 | –1.25 | –1.25 | –1.25 | –1.25 |
| Caribou | 0.19 | –0.07 | –0.47 | –0.36 | –0.37 | –0.53 |
| Barnes | 0.40 | –1.00 | 0.33 | –0.04 | 0.33 | 0.28 |
| Tifton | 0.49 | –0.05 | –0.86 | –1.26 | 0.43 | 0.27 |
| AVERAGE | 0.46 | –0.37 | –0.38 | –0.18 | –0.25 | –0.16 |

* OPT = calibrated value.
RAEQ = calculated using equation 5.
TABLE = from table 4 of Rawls and Brakensiek (1982).
TRI = from modified textural triangle given in Rawls and Brakensiek (1985).
EPIC = calculated using equation 7.
RSEQ = calculated using equation 8.

"TRI" method uses the modified textural triangle given in Rawls and Brakensiek (1985). In this method, $K_{sat}$ is a function of sand and clay and can be determined by reading the conductivity directly from a modified textural triangle. The "EPIC" method uses the equation developed for the EPIC model (Sharpley and Williams, 1990). This equation states:

$$K_{sat} = \frac{1270(1-Cl)(SS_f)}{100(1-Cl)+\exp[11.45-9.7\,(1-Cl)]} \quad (7)$$

where $SS_f$ is the soil strength factor. The soil strength factor is intended to represent compacted soil sublayers, therefore, $SS_f$ was set equal to one for the upper soil layer in our study. The final estimation equation, "RSEQ" is given by:

$$K_{sat} = 12.12\,(\phi_e - \theta_{fc})^{4.5} + 26\,\frac{CEC}{Cl} + 0.32\,OM - Cl + 2\,Sa \quad (8)$$

where

$\phi_{fc}$ = moisture content at field capacity (L/L)
OM = % organic matter
CEC = cation exchange capacity of the soil (cmol/kg)

This equation was developed as part of WEPP. It was derived using regression techniques on rainfall simulator runoff plot data collected as part of the WEPP cropland soil field erodibility experiments (Elliot et al., 1989).

### MODEL EFFICIENCY

Nash and Sutcliffe (1970) introduced the concept of model efficiency which is similar to the correlation coefficient from linear regression, $r^2$. It is defined as:

$$E = 1 - \frac{\sum_{t=1}^{n} (Y_t - P_t)^2}{\sum_{t=1}^{n} (Y_t - \overline{Y})^2} \quad (9)$$

where E is the model efficiency, $Y_t$ and $P_t$ are the observed and predicted output for event t, respectively, and $\overline{Y}$ is the average of the observed values. An important difference between the model efficiency and $r^2$ values is that the model efficiency is comparing the predicted values to the 1:1 line between measured and predicted values rather than the best regression line through the points. The model efficiency will always be lower than the correlation coefficient and the amount which it is lower is indicative of a bias in the model. Much like the correlation coefficient, a value of one indicates perfect agreement between the measured and predicted values and decreasing values indicate less correlation between the two. Note that the model efficiency can be negative. If this occurs it indicates that the average value of the output is a better estimate than the model prediction.

## RESULTS AND DISCUSSION

The calibration procedure described above was used to find the calibrated values of hydraulic conductivity, $K_{opt}$. These values represent the "best" values of effective hydraulic conductivity for the given series of events. This method could generally locate the optimum value of the hydraulic conductivity to 0.01 mm/h in less than 20 iterations. Figure 1 shows a plot of the response of the optiminization algorithm at each of the sites with a search range of 0.07 to 10 mm/h (none were outside this range). In this figure, each point represents one iteration of the search algorithm. It is apparent from these results that a good approximate value of the conductivity can usually be found in less than 10 iterations and most of the subsequent iterations are used to refine this estimate to the desired accuracy. It is also interesting to note the response of the LSE term to changes in conductivity. While the response appears different at each of the various sites due to differences in the number and sizes of the events contributing to this error term, it is evident that in the area near the minimum LSE, small changes in the conductivity do not have significant effects on the response of the error term. This is important as it shows that good estimates could be obtained without optimizing to a high degree of accuracy.

All of the measured values of hydraulic conductivity were much higher than the calibrated values. Bouwer (1966) showed that $K_e$ should be less than the saturated value, $K_{sat}$, because of entrapped air and suggested that it be estimated as approximately half of $K_{sat}$. For the two soils with measured values of saturated hydraulic conductivity from soil cores (Egan and Barnes), the

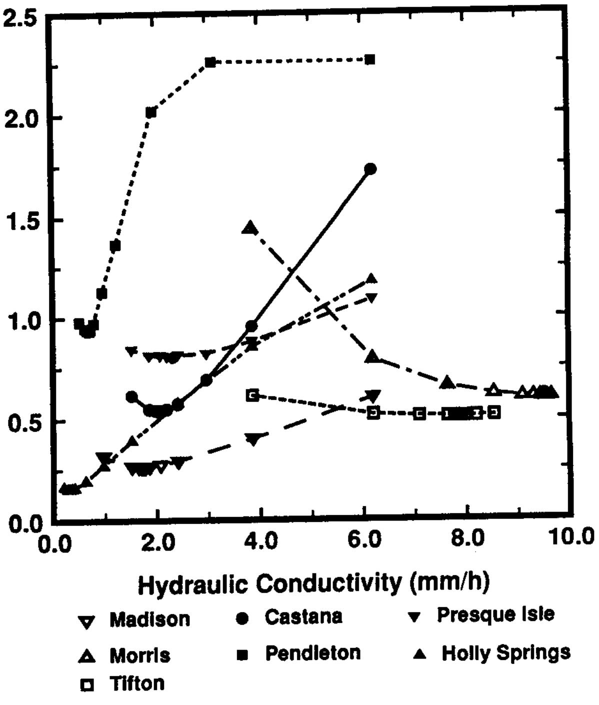

Figure 1–Response of the LSE between measured and G&A/WEPP predicted runoff volumes for each location. Each point represents one iteration of the optimization algorithm. Residual variance calculated as $\Sigma(Y-\overline{Y})^2$.

calibrated effective hydraulic conductivities were approximate one tenth and one quarter of the measured values. Others have suggested methods for obtaining $K_e$ based on the unsaturated hydraulic conductivity function or other soil parameters (Brakensiek and Onstad, 1977; Rawls and Brakensiek, 1983). The fact that the Green-Ampt hydraulic conductivity has physical significance and can be calculated from soil properties is advantageous, however, the use of parameters obtained from fitting field data will usually produce more reliable results as these measurements tend to lump the effects of heterogeneities, crusting, macroporosity, and other natural phenomena (Skaggs and Khaleel, 1982). The hydraulic conductivities which were measured under simulated rainfall were generally closer to the calibrated values than the hydraulic conductivities measured from soil cores, however, they were still higher than the calibrated values. This should be expected as these values were measured under freshly tilled conditions. As the soil consolidates and surface crust form, one would expect the hydraulic conductivity to decrease. The calibrated values represent the average conditions over the entire range of rainfall events and should be somewhat less than the hydraulic conductivity immediately after tillage.

The hydraulic conductivities estimated using each of the methods presented earlier and the model efficiencies obtained using these estimates are given in tables 3 and 4. Overall, none of the estimation methods performed consistently better than the others. In terms of predicting the closest to the calibrated values, the equation of Rawls et al. (1989) was the best at three sites while the method from EPIC was best at two sites. However, in terms of the model efficiencies using these estimated values, the equation of Rawls et al. (1989) performed poorly, with an average model efficiency of –0.37. This equation tended to underpredict the values for $K_e$ which resulted in overpredictions of runoff. Since the error associated with an underprediction of runoff is bounded by zero while the error associated with an overprediction is limited by the rainfall amount, in terms of model efficiency, the model will perform much better with values of $K_e$ which are too high rather than too low. For example, the Egan soil had an optimized $K_e$ of 1.73. The Rawls equation estimation (0.23) was closer to this value than the estimation from EPIC (4.34), yet the model efficiency using the EPIC estimate (0.56) was much higher than that using the estimate from the Rawls equation (0.24).

All of the procedures estimated values of $K_e$ which were much higher than the calibrated value for the Tifton loamy sand. The calibrated value seems low compared to the measured value as well. This could indicate that some external factor such as soil crusting or a high water table is reducing the effective hydraulic conductivity and the G&A/WEPP model is not accounting for the reduction. Generally, the Rawls estimation equation tended to underestimate the values of $K_e$ while the method presented in EPIC as well as the RSEQ equation tended to overestimate it. One would expect the estimates obtained from the equations to be slightly higher than the calibrated values as they are intended to represent uncrusted and saturated conditions rather than effective values. The equations which incorporated more information on the soils did not perform as well as some of the simpler methods such as the equation in EPIC which only uses percent clay and the triangle nomograph which uses clay and sand. The fact that the average model efficiency was negative for all of the parameter estimation routines indicates that using an average value of runoff would produce better estimates of runoff than G&A/WEPP model did using these estimated parameters. This indicates the importance of obtaining reliable estimates of $K_e$ by calibrating it to field measurements of infiltration data.

Another objective of this study was to analyze the results using calibrated values of hydraulic conductivity (table 5). The average error indicated that at most of the sites the G&A/WEPP model tended to slightly underpredict runoff while the average magnitude of the error was a better indication of how well the estimates of runoff matched the predicted values. The model efficiencies indicated that at most of the sites the G&A/WEPP model performed fairly well using calibrated values of $K_e$. The unusually poor results from Pendleton were probably due to the fact that the measured values of runoff were so low. These small events generally produced worse results as there were many more events where the G&A/WEPP model did not predict runoff for measured events and other factors such as depressional storage became more important on these small events. Other factors which contributed to the poor results from the Pendleton data included larger differences between the replicates, the fact that most of the events occurred during the winter and under low intensity rainfall where other factors may be significant and that the measured data did not appear to be collected as regularly as it was at other sites.

Most of the sites exhibited a trend which is evident in the plots of the measured values against predicted values and the residuals (fig. 2). The model tended to overpredict runoff from the smaller events while it underpredicted runoff from the larger events. The results from the regression analysis also display this trend. Regression on the results from an unbiased model would produce an intercept of zero and a slope of one. At every site in the study, the slope of the regression line was less than one and six of the seven sites had intercepts which were greater than zero. Therefore, the results for all of the sites are biased upwards for the smaller events and downwards for the larger events. This bias cannot be corrected through calibration and is inherit to the Green-Ampt equation or some component in WEPP model. The fact that the total runoff from all of the events was underpredicted at all of

**Table 5. Statistics of output using calibrated hydraulic conductivities for each location**

| Soil | Events | Measured Runoff* (mm) | Average Error† (mm) | Regression Stats Slope | Int. | $r^2$ | Model Effic. |
|---|---|---|---|---|---|---|---|
| Providence | 208 | 15.2±17.3 | –0.63 (4.7±5.0) | 0.87 | 1.39 | 0.84 | 0.84 |
| Egan | 60 | 8.0±11.8 | –0.90 (4.1±4.4) | 0.69 | 1.57 | 0.75 | 0.74 |
| Monona | 90 | 11.5±8.4 | –1.58 (4.7±4.2) | 0.82 | 0.50 | 0.59 | 0.46 |
| Thatuna | 82 | 3.2±2.8 | –1.42 (2.1±1.7) | 0.61 | –0.18 | 0.41 | 0.07 |
| Caribou | 101 | 6.9±8.4 | –1.96 (4.9±5.8) | 0.55 | 1.12 | 0.36 | 0.19 |
| Barnes | 72 | 5.6±6.9 | –1.66 (3.8±3.8) | 0.69 | 0.05 | 0.52 | 0.40 |
| Tifton | 72 | 19.6±17.5 | –3.27 (8.8±8.8) | 0.79 | 0.77 | 0.59 | 0.49 |

* Measured runoff ± one standard deviation.

† Average error (average of the absolute values of the error ± one standard deviation).

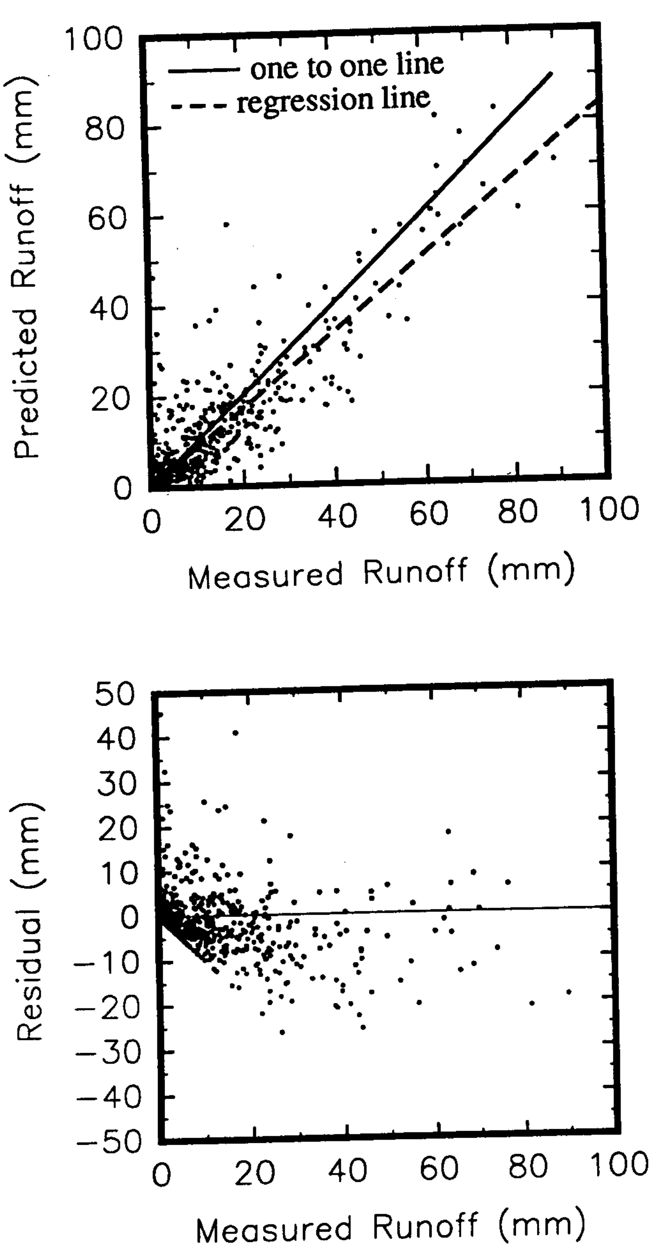

**Figure 2–Measured runoff plotted against WEPP predicted runoff and residuals for all locations using calibrated values of hydraulic conductivity. Regression equation is $Y = 0.83X + 0.34$, $n = 683$, $r^2 = 0.75$.**

the sites may also be attributable to this bias and the fact that LSE rather than the absolute error was used as the objective function.

One possible explanation for the bias may be that for the small events, less of the plot is contributing runoff than for the larger events. Since the model assumes that the entire plot is contributing to the runoff volume, for a given $K_e$, the model will overestimate the runoff on these smaller events. Unfortunately, with the data used in this study it was not possible to determine this partial area response, however, it is mentioned as a possible source of error. Other studies have indicated that if the rainfall distribution includes relatively long periods of low intensity rainfall or zero rainfall, the wetted profile will redistribute and assumptions inherit to the G&A equation (slug flow with a sharp wetting front) will not be met (Skaggs and Khaleel, 1982). Although the rainfall disaggregation routines in WEPP transform all of the rainfall events into single peak storms, many of the larger events do have longer durations, likely including periods of low intensity rainfall. Even though the peak rainfall intensities and storm duration will match the characteristics of the actual storm, this disaggregation and the periods of low rainfall intensity for the larger storms could be contributing to the underestimation of runoff on these larger events.

## CONCLUSIONS

- A method for calibrating the hydraulic conductivity parameter in the Green-Ampt equation on an event basis using the continuous simulation WEPP model was developed. This method was tested and it was shown that it could successfully locate optimum values of the hydraulic conductivity to 0.01 mm/h in a maximum of 15 to 20 iterations.
- The calibrated values were all lower than measured values of hydraulic conductivity. The hydraulic conductivities measured under simulated rainfall were closer to the calibrated values than the two values measured using a constant head permeameter on soil cores.
- Five different methods of estimating the hydraulic conductivity based on soil properties were compared to the calibrated values. None of the methods could consistently perform better than the others. Model efficiencies for predicting runoff using these estimated values were often less than zero indicating that an average value of runoff could be used to outperform the Green-Ampt/WEPP model using these parameters.
- Using optimized values of hydraulic conductivity, the average Nash-Sutcliffe model efficiency for the Green-Ampt/WEPP predictions of runoff on an event basis was 0.46. The Green-Ampt/WEPP model tended to overpredict runoff on the small events and underpredict runoff on the larger events.

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