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RUNOFF USING GREEN-AMPT AND SCS CURVE NUMBER PROCEDURES AND ITS EFFECT ON THE CERES-MAIZE MODEL

by

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SUMMARY:

CERES-Maize was run with historical rainfall for 6 years. Each day when rainfall occurred was then simulated with a Green-Ampt procedure using initial soil water conditions CERES-Maize. CERES-Maize tended to predict lower runoff and higher infiltrations than Green-Ampt. For one event the CERES-Maize model predicted 40% more infiltration than the CERES-BP model. Implementation of improved infiltration procedures could improve CERES-Maize predictions. The adjusted infiltration for the CERES-Maize model improved the yield predictions from 12 to 26% for the three soils studied.

KEYWORDS:

Infiltration, runoff, models, curve number, Green-Ampt

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INTRODUCTION

Simulations by CERES-Maize for the 1986 drought were found to overestimate known yields by a factor of 2 or more (Sadler, et al., 1991). Further study showed that one storm (94.5 mm in 52 min) replenished the entire modeled soil profile, which resulted in higher simulated than observed yields. This suggested that runoff and infiltration were not adequately accounted for in the CERES-Maize model. Supporting this were observations of erosion in the field after short, intense storms, although the simulated runoff was essentially nil (E. J. Sadler, personal communication, 1986). Additionally, published data on infiltration for these soils (Beal et. al, 1966) show much lower infiltration rates than were estimated in CERES-Maize. These observations suggest that CERES-Maize may not be able to adequately partition runoff and infiltration for the high-intensity rainfalls common during the summer growing season in the Southeast. The normal result of this type of error was to simulate less-severe soil moisture deficit conditions than actually occurred.

Over-prediction of actual yields may affect conclusions of climate change scenarios that use CERES-Maize to simulate crop production conditions, particularly for drought. In studies by Robertson et al. (1988), temperature and precipitation anomalies predicted by global climatic models were impressed upon typical weather, and CERES-Maize was run for both the typical and anomalous weather. The difference in yield was attributed to the climate shift. With respect to observations during the 1986 drought mentioned above, confidence in these predictions requires confidence in the runoff methods used. Rain during these periods of drought may be short, high-intensity rainfalls that the models may not adequately simulate the partitioning of rainfall and runoff.

Because the simulations appeared to overestimate infiltration during intense rain, it was proposed that a procedure that depended upon rainfall rates during the storm, rather than upon total rainfall, might have potential in solving the problem. One such procedure is based on the Green-Ampt equations (Green and Ampt, 1911), which have been encoded for use in simulation models such as CREAMS (Knisel, 1980). Inputs for this model include breakpoint rainfall data, which are a time-dependent record of accumulated rainfall during a storm. Such data have been collected at the Florence station since 1983. This type of rainfall data may not be available for all areas. Availability of these data and experience with both CERES-Maize and the CREAMS models suggested that the differences between these methods could be readily studied.

Rawls and Brakensiek (1986) compared Green-Ampt and SCS Curve Number runoff volume predictions on 330 runoff events from 17 small watersheds. They found that the Green-Ampt procedure predicted runoff volumes with more accuracy than the curve number procedure.

The significance of the runoff/infiltration partitioning coefficient in the water balance of agricultural crops is apparent to most practitioners, but it is not known how serious potential errors might be, nor how often the rainfall characteristics, soil moisture, and crop stage interact to cause significant errors in final yield. It would seem that summer conditions across the Southeast would be susceptible, however, since thunderstorms provide a significant portion of the total rainfall during that time. Additionally, simulations of effect of global warming have, as input, increased temperatures and oftentimes reduced rainfall, both of which would likely increase the probability of drought conditions (Waggoner, 1991). This study was conducted because of the increased probability of error and because of the increased importance of the correct estimation of storm runoff/infiltration amounts on estimation of crop yields, particularly under conditions of drought.

The objectives of this work were: (1) to compare rainfall-runoff simulations using the SCS curve number procedure and the Green-Ampt procedure as implemented in the agricultural models CERES-Maize and CREAMS, and; (2) to determine the effect of refinements in storm runoff/infiltration partitioning on the final results of hydrologic simulations of yield estimates using the CERES-Maize model.

CURVE NUMBER PROCEDURE

The CERES-Maize model (Jones and Kiniry, 1986) is a user-oriented, daily-incrementing simulation model that simulates the effects of genotype, weather, and soil properties on maize growth, development, and yield. Runoff and infiltration in CERES-Maize are simulated by the SCS Curve Number procedure (USDA, Soil Conservation Service, 1972), implemented in FORTRAN, and imbedded within the model (Jones and Kiniry, 1986). The form of the SCS Curve Number procedure used in CERES-Maize was developed for CREAMS (Smith and Williams, 1980; Knisel, 1980) and modified slightly (Jones and Kiniry, 1986) to fit the needs of the CERES-Maize model.

The daily runoff for both CREAMS hydrology option 1 (CREAMS-CN) and CERES-Maize is calculated using the SCS runoff equation which is

$$Q = \frac{(P - 0.2S)^2}{(P - 0.8S)} \qquad P > 0.2S \tag{1}$$

where Q is runoff, P is rainfall, and S is a watershed storage parameter, all having units of depth (mm). The storage parameter is calculated as

$$S = S_{mx} \left[1.0 - \sum W_i \frac{SM_i}{UL_i} \right] \tag{2}$$

where SM is the soil water content (mm), UL is the upper limit of soil water storage in the profile (mm), S_{mx} is the maximum value of S, and W is a weighting factor used in determining runoff. The maximum value for S is determined from the SCS equation relating it to curve number as

$$S_{mx} = \frac{1000}{CNI} - 10 \tag{3}$$

where CNI is the curve number for antecedent moisture condition 1. The weighting factors decrease with depth according to the equation

$$W_i = 1.016 \left[e^{-4.16\left(\frac{D_{i-1}}{RD}\right)} - e^{-4.16\left(\frac{D_i}{RD}\right)} \right] \tag{4}$$

where D_i is the depth to the bottom of storage i (mm), and RD is the root zone depth (mm). The curve number for condition 2 (CNII) is input for both models and is converted by the model to the equivalent CNI value using the equation

$$CNI = -16.91 + 1.348 \times CNII - 0.01379 \times CNII^2 + 0.0001177 \times CNII^3 \quad (5)$$

Differences between the implementation of the curve number procedure for the two models include the number of soil layers that each model uses. In CERES-Maize, up to 10 layers of soil information can be input. These are expected to describe the natural soil horizons, subject to some computational constraints. The soil profile defined in CERES-Maize should not be less than 2 m, unless there is an impermeable layer at a shallower depth. Additional CERES-Maize guidelines for soil layers are that no layer in the top 0.3 m should be thicker than 0.15 m, and that no layer below the top 0.3 m should be thicker than 0.3 m. The CREAMS-CN model uses seven layers: the top layer is 1/36 of the soil profile depth, the second is 5/36 of the profile depth, and the remaining 5 layers are each 1/6 of the profile depth. The CREAMS-CN model requires only the maximum rooting depth for input, and it then calculates the soil depths for the seven layers.

The thickness, lower limit of plant-extractable water, drained upper limit, saturated water content, initial water content, and a root weighting factor are input for each layer for CERES-Maize. The CREAMS-CN model requires the plant available soil water storage for each of the 7 soil layers. Whole profile inputs for CREAMS-CN are the effective saturated conductivity (mm/hr), pore space filled at field capacity, soil porosity, and immobile soil water content. The initial condition for the CREAMS-CN model is the plant-available water storage filled when the simulation begins.

GREEN-AMPT PROCEDURE

The CREAMS model also has as an option to simulate runoff using an implementation of the Green-Ampt (1911) method (referred to as CREAMS-BP) that calculates runoff from and infiltration into the soil profile using breakpoint rainfall data (Knisel, 1980). The soil profile in the CREAMS-BP model is divided into two layers. The surface layer is typically a thin layer, and the infiltration model is sensitive to its conditions at the start of the rainfall. The lower zone consists of the remainder of the profile. The CREAMS-BP model requires both the depth of the surface layer and the maximum rooting depth used in the CREAMS-CN model. The Green-Ampt relation used in the CREAMS model is

$$F = \frac{H_c \, \phi \, (S_o - S_i) \, K_s}{f - K_s} \quad (6)$$

where S is the saturation index, ϕ is the porosity, K_s is the effective saturated conductivity (mm/hr), H_c is the effective capillary tension (mm), f is the infiltration rate (mm/hr), and F is the cumulative depth of infiltration (mm). Smith and Williams (1980) provide a detailed discussion of the implementation of the Green-Ampt method in CREAMS.

SIMULATIONS

All simulations were run on a VAX 11/750 Minicomputer[1] under the VMS operating system version 5.4. The CERES-Maize and CREAMS models, written in FORTRAN-77, were implemented on the VAX computer. Data manipulation programs were implemented in FORTRAN-77 and statistical analysis was accomplished using SAS version 6.06 (SAS, 1990).

Weather data for the simulations were obtained from the weather station at the Coastal Plain Soil and Water Conservation Research Center in Florence, SC. The weather station (Sadler and Camp, 1985) was located 300 m SW of an 8-ha field for which the soil mapping units were characterized and for which corn yield was collected in 1985, 1986, and 1988 (Karlen et al, 1990). Solar irradiance, air temperature extremes, and rainfall totals were summarized into the required formats for CERES-Maize and CREAMS-CN. Rainfall at this station was measured with a tipping-bucket rain gauge, and the number of tips, if any, was recorded each minute. These data were used to create the accumulated rain curve required for input to the CREAMS-BP model.

The CERES-Maize model was as described by Jones and Kiniry (1986) except for modifications made by the authors to print the full soil water balance. Soil parameter files in CERES-Maize format describing 18 soil map units within the 8-ha field study were developed by Sadler et al. (1991). They estimated soil physical properties from SCS soil pedon descriptions, state experiment station bulletins, and local measurements. An example CERES-Maize soil file is shown in Table 1.

The CERES-Maize input and output files were converted into the input formats for the CREAMS models (CREAMS-CN and CREAMS-BP) with a conversion program written in FORTRAN-77 for this purpose. Soil descriptions, properties, and soil water status of the profile were converted or calculated. The soil profile layers from CERES-Maize were interpolated to fit the predetermined layers for both the CREAMS-CN model and the CREAMS-BP model. Parameters required for the CREAMS models that were not available from the CERES-Maize data files were estimated using the CREAMS guidelines and the soil descriptions. Example soil files for both CREAMS options are shown in Tables 2 and 3.

Parallel Simulations

The CERES-Maize model was run with historical rainfall for six years, 1985-1990. Each day when rain occurred was then simulated with both CREAMS-CN and CREAMS-BP. The soil water content predicted by CERES-Maize for the day before each rain was input to the CREAMS models. This eliminated any model differences in prior rainfall events causing a bias in soil water content. Both CREAMS-CN and CREAMS-BP were run this way for the same years as was CERES-Maize.

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[1] Mention of tradenames is for the convenience of the reader and is not intended to imply endorsement over other products that may be applicable.

Sensitivity Analysis

Sensitivity analyses were run on the CREAMS-CN, CREAMS-BP, and CERES-Maize models. Sensitivity to varying rainfall totals (6, 12, 25, 50, 75, 100 mm) in a single time period (1 hr) and to varying duration (1, 2, 4, 6, 12, 24 hrs) with a single rainfall depth (100 mm) were simulated. Accumulated rainfalls were simulated using a standard distribution hyetograph (South Florida Water Management District, 1987) for varying rainfall depths and durations. These sensitivity analyses were repeated for three soils: a Norfolk loamy fine sand, NkA (fine-loamy, siliceous, thermic Typic Paleudult), a Bonneau loamy fine sand, BnA (loamy, siliceous, thermic Grossarenic Paleudult), and a Coxville loam, Cx (clayey, kaolinitic, thermic Typic Paleaquult). Initial soil moisture conditions for the simulations were taken from CERES-Maize simulations of conditions prior to the 1986 storm on day 150 for each of the three soils (Cx, NkA, BnA). Yields predicted by the CERES-Maize model were compared for the varying rainfall inputs.

Adjusted Simulations

Sensitivity analysis results were used to adjust inputs to the CERES-Maize model to account for differences in rainfall/runoff/infiltration. The rainfall inputs to the CERES-Maize model were reduced so that the simulated infiltration would match that of the CREAMS-BP model. The adjustment procedure is illustrated in Figure 1. Infiltration from CREAMS-BP was determined for the actual rainfall, then the rainfall needed to produce the same infiltration from CERES-Maize was estimated. CERES-Maize was run with these estimates for each rainfall event. Iteration produced successively better estimates of infiltration for CERES-Maize until it matched the CREAMS-BP infiltration within 1 mm for each rain.

RESULTS AND DISCUSSION

Parallel Simulations

Simulation results for the three models showed that infiltration and runoff were season dependent for all the models. For this discussion, seasons were classified into four periods during the year: pre-planting, growing season, dry-down (arbitrarily defined as 3 weeks starting at physiological maturity), and post-harvest. The infiltration during the pre-planting and post-harvest periods was consistently lower for the CERES-Maize model than for the CREAMS-CN and CREAMS-BP models. The cause of these non-growing season differences has yet to be determined. The growing season, being the most important for studying the effects of infiltration and runoff on simulated corn yields, was the primary focus of this research. During the growing season and dry-down, runoff simulated by the three models was similar in most instances, although the CERES-Maize model tended to predict lower runoff and higher infiltration than the CREAMS-BP model (Figures 2 and 3). Extreme events and extended dry periods during the growing season produced results that were notably different for each of the models (Figure 2, days 150 and 210). During the severe 1986 drought, one storm produced 94.5 mm of rainfall in 52 min on day 150. The CERES-Maize model predicted that 78% of the rainfall infiltrated into the soil, the CREAMS-CN model predicted less infiltration (72%), but the CREAMS-BP model predicted less than half (40%) of the rainfall was infiltrated. Extended droughts may be expected to become more common if current global climate change predictions are correct. If such is the case, we would need to have models that would perform well under these conditions.

Sensitivity Analyses

The simulations with varying rainfall totals and durations illustrate the sensitivity of the models to these inputs. Simulations were conducted using initial conditions prior to the storm on day 150 of 1986 and therefore represent very dry conditions. For short, intense rainfall events, the CREAMS-BP model predicted much more runoff and less infiltration than the daily curve number models (Figure 4). For longer durations and lower rates (12 and 24 hr simulations), the CREAMS-BP model-predicted runoff approached the curve number (CERES-Maize and CREAMS-CN) models. Data for BnA and Cx, not shown, indicate somewhat less infiltration at higher rain totals. These differences between the curve number models (CERES-Maize and CREAMS-CN) and the Green-Ampt (CREAMS-BP) model show that differences may exceed 50% for a single storm. The differences between the CREAMS-CN model and the CERES-Maize model could be due to interpolation of the soil profile data. The CREAMS-BP model predicted much more runoff than either curve number model.

The simulations with the CERES-Maize model using varying rainfall on day 150, 1986, were conducted to illustrate the effects of varied infiltration. A range from 6 to 100 mm produced a range of infiltration from 6 to 50 mm (BnA and Cx) or 75 mm (NkA). The CERES-Maize model predicted increasing yields for the increased rainfall and infiltrations, Figure 5. The predicted yields ranged from ~1900 kg/ha with 6 mm of infiltration to ~5200 kg/ha with 75 mm of infiltration. All three soils produced increasing yields as a function of infiltration, with the BnA soil having the greatest sensitivity to infiltration during this rain.

Adjusted Simulations

The adjustment of rainfall input to the CERES-Maize model allowed determination of the effect of seasonal infiltration calculated by these two methods on final yield. The results for all three soils are presented in Table 4. Implementing the Green-Ampt procedure in CERES-Maize would reduce the predicted yield by about 12 to 26% for these three soils.

SUMMARY AND CONCLUSIONS

The CERES-Maize model was run with historical rainfall for 6 years. Each day when rainfall occurred was then simulated with both the CREAMS hydrology options 1 (SCS Curve Number, CREAMS-CN) and 2 (Green-Ampt, CREAMS-BP) using initial soil water conditions from the CERES-Maize model output. During the growing season, infiltration simulated by the 3 models was similar in most instances. CERES-Maize tended to predict lower runoff and higher infiltrations than CREAMS-BP. For extreme events, CERES-Maize predicted more infiltration and less runoff than the CREAMS-BP model. For one event, the CREAMS-BP model predicted 40% less infiltration than the CERES-Maize model.

Differences in predictive efficacy are attributed to differences in how the soil profile data are handled.

A sensitivity analysis showed that for short, intense rainfalls, the Green-Ampt (CREAMS-BP) model predicted less infiltration and greater runoff than either curve number model. The CREAMS-BP model, which provides finer resolution of rainfall inputs, showed significantly greater runoff volumes for short duration, intense storm events that are characteristic of the region, particularly within the growing season. The CERES-Maize model showed substantial variation in crop yields with varying infiltration for a single storm event within the growing season. Results from the yield data of this study indicate that the magnitude of errors in predicted corn yields obtained using this version of CERES-Maize model could dramatically affect conclusions regarding the impact of climatic change on crop production, particularly for those scenarios involving drought conditions which is perhaps one of the primary concerns of climatic modelers.

Implementation of improved infiltration procedures could improve the accuracy of CERES-Maize. The adjusted infiltration for the CERES-Maize model improved the yield predictions from 12 to 26% for the three soils studied.

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Table 1. Example CERES-Maize data file for Nka soil with initial conditions for day 1, 1986.

```
NkA - 1986, SW=Spec
 94  5.44  3.81 34.20  1  1  0 2.00  1
PIONEER 3165      255. .760 685. 834.0 10.00
  0   0  2627. .000    0.   0.  0.0     0.
.20  7.5 0.26 80.0
 9.0 .054 .123 .260 1.00 .070
 8.0 .052 .127 .261 0.77 .130
13.0 .061 .162 .260 0.63 .150
21.0 .162 .271 .353 0.44 .260
30.0 .175 .283 .332 0.27 .270
28.0 .173 .283 .332 0.15 .240
30.0 .171 .283 .332 0.08 .190
30.0 .171 .283 .332 0.05 .190
30.0 .171 .283 .332 0.03 .190
 0000
```

Table 2. Example CREAMS Curve Number data file for NkA soil on day 150, 1986.

```
CREAMS HYDROLOGY PARAMETERS
DAILY RAINFALL MODEL
NkA - 1986, SW=Spec
  86150       1       0       1       0
   1.00   0.200   0.661   0.209   3.750   0.394   0.154
  0.200  80.000   0.022   2.100  78.346
   0.15    0.98    1.42    1.43    1.46    1.47    1.45
  42.00   50.83   54.84   63.99   71.09   79.11   83.04   76.56   73.72   64.48
  57.71   46.01
 232.74  261.41  414.49  553.93  549.93  554.97  569.81  429.32  408.21  307.45
 162.41  196.52
  1.000
      1   0.000
     99   0.000
    149   2.380
    150   2.530
    200   0.900
    201   0.000
    366   0.000
     -1       0       0
```

Table 3. Example CREAMS Green-Ampt data file for NkA soil on day 150, 1986.

```
CREAMS HYDROLOGY PARAMETERS
BREAKPOINT RAINFALL MODEL
NkA - 1986, SW=Spec
  86150        1        0        2        0
   1.00    0.200    0.661    0.209    3.750    0.394    0.154
  2.194   71.805   13.000    0.030    0.015  100.000
  42.00    50.83    54.84    63.99    71.09    79.11    83.04    76.56    73.72    64.48
  57.71    46.01
 232.74   261.41   414.49   553.93   549.93   554.97   569.81   429.32   408.21   307.45
 162.41   196.52
  1.000
      1    0.000
     99    0.000
    149    2.380
    150    2.530
    200    0.900
    201    0.000
    366    0.000
     -1        0        0
```

Table 4. Effect of adjusted infiltration on CERES-Maize (CM) simulated final yield.

	Soil			
	NkA	Cx	BnA	Units
Actual Rain	94.5	94.5	94.5	mm
Original CERES-Maize Infiltration	72.7	49.3	49.1	mm
Original CERES-Maize Runoff	22.7	46.1	45.4	mm
Original CERES-Maize Simulated Yield	5238	4129	4735	kg/ha
CREAMS-BP Infiltration	37.5	40.1	30.7	mm
Adjusted Rain	38.5	60.0	38.5	mm
Adjusted CERES-Maize Infiltration	37.6	39.8	31.3	mm
Adjusted CERES-Maize Runoff	0.9	20.2	7.2	mm
Adjusted CERES-Maize Yield	3891	3652	3581	kg/ha
Measured Yield	2627	556	-	kg/ha
Effect of Reduced Infiltration	26	12	24	% of original CERES-Maize yield
	52	13	-	% of deviation from measured yield

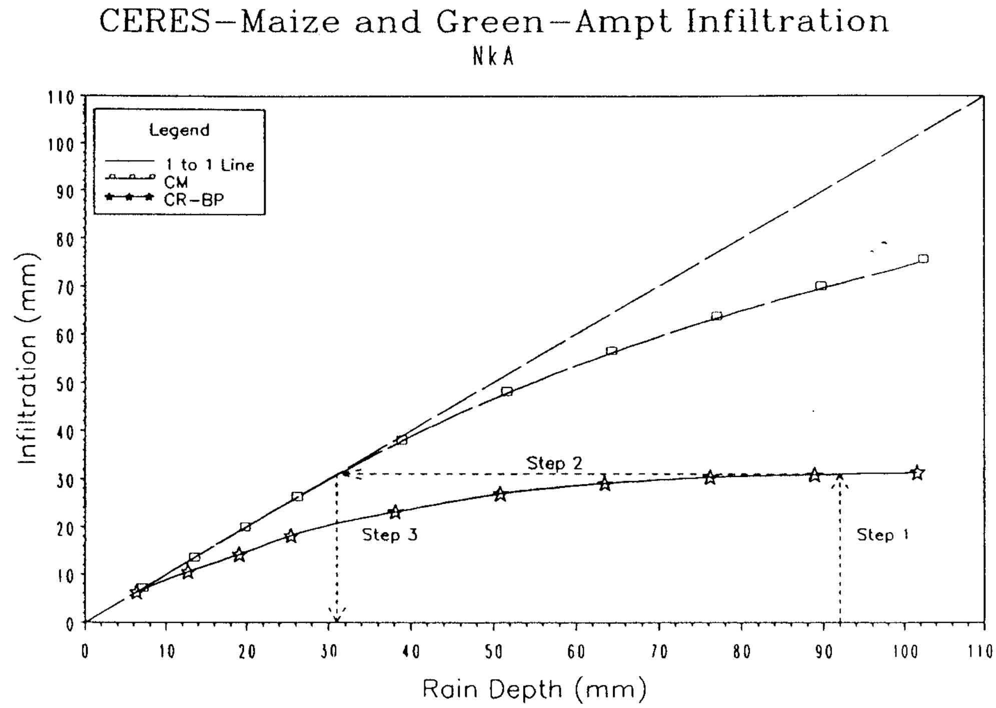

Figure 1. Example correction procedure for correcting CERES-Maize (CM) rainfall from the Green-Ampt (CREAMS-BP) infiltration predictions.

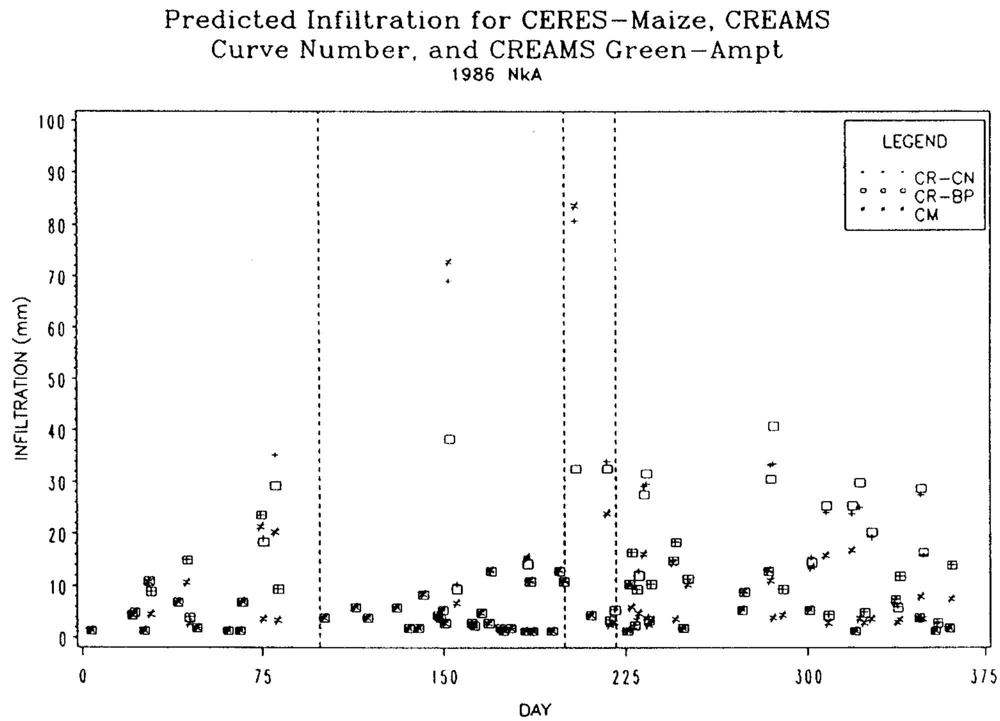

Figure 2. CERES-Maize (CM), CREAMS Curve Number (CREAMS-CN), and CREAMS Green-Ampt (CREAMS-BP) infiltration for an NkA soil, 1986.

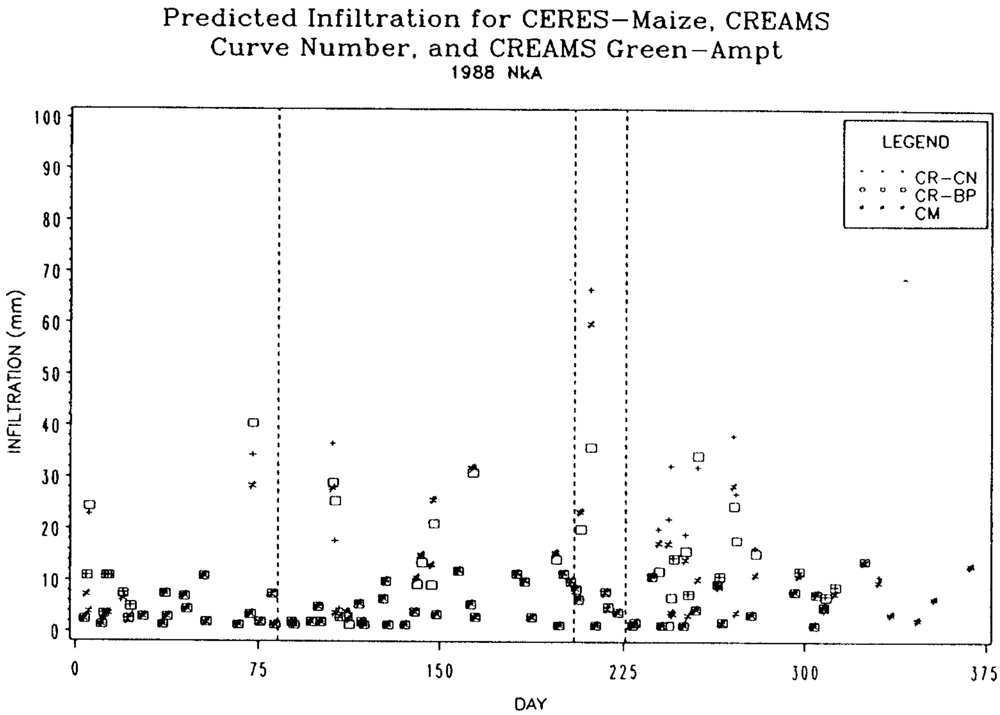

Figure 3. CERES-Maize (CM), CREAMS Curve Number (CREAMS-CN), and CREAMS Green-Ampt (CREAMS-BP) infiltration for an NkA soil, 1988.

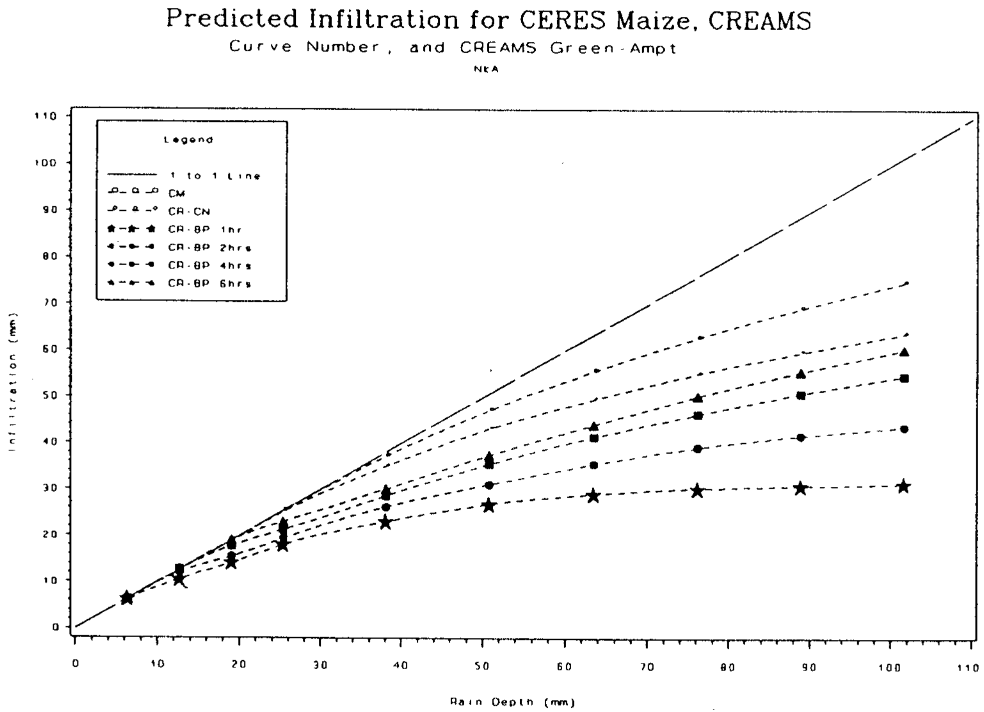

Figure 4. Predicted infiltrations for CERES-Maize (CM), CREAMS Curve Number (CREAMS-CN), and CREAMS Green-Ampt (CREAMS-BP) for varying rainfalls and durations for an NkA soil.

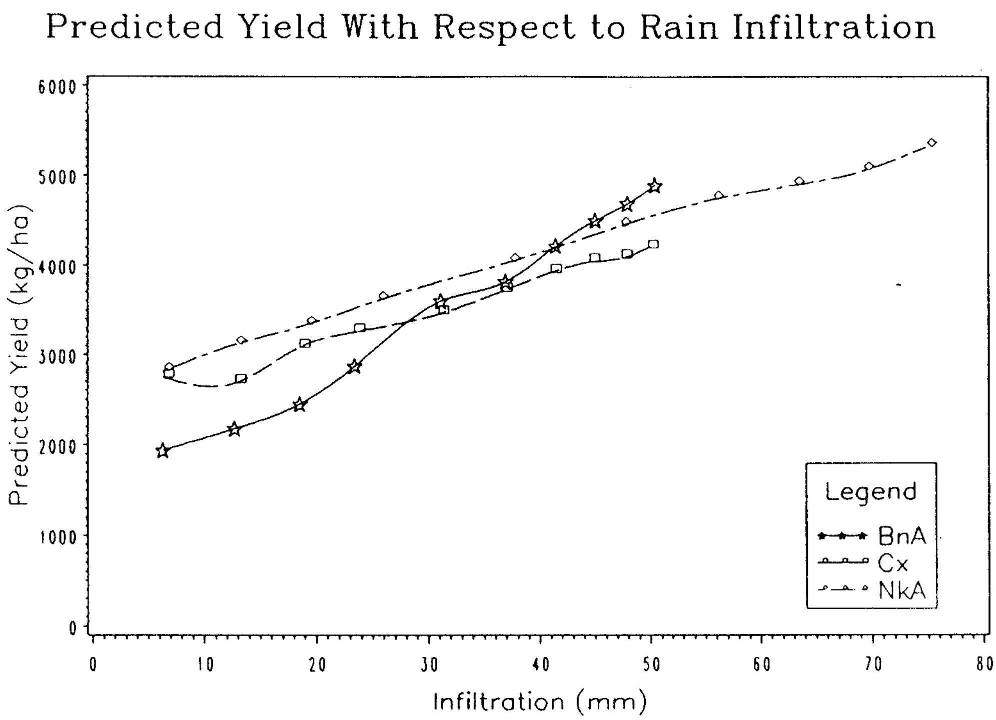

Figure 5. Predicted yields for CERES-Maize (CM) for varying infiltration.