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Simulating Surface Runoff Volume in Southern Louisiana with DRAINMOD[1]

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ABSTRAK

Model simulasi pengurusan air, DRAINMOD, telah digunakan untuk membuat simulasi air lari dari petak yang mempunyai saliran bawah tanah dan petak yang tidak mempunyai saliran bawah tanah. Data yang telah dikumpulkan selama tujuh tahun (1981-87) digunakan dalam kajian ini. Anggaran jumlah air lari yang dicadangkan oleh model adalah melebihi sebanyak 7.7% bagi petak yang mempunyai saliran bawah tanah dan 25.1% bagi petak yang tidak mempunyai saliran bawah tanah berbanding dengan jumlah air lari sebenar yang direkodkan. Secara umumnya, model berupaya untuk menganggar jumlah air lari di selatan Louisiana.

ABSTRACT

The water management simulation model, DRAINMOD, was used to simulate surface runoff volume from a subsurface-drained plot and a non-subsurface-drained plot in southern Louisiana. Seven years (1981-87) of recorded data were used in this study. The model overestimated the total surface runoff volume by 7.7% and 25.1% from the subsurface-drained plot and the non-subsurface-drained plot, respectively. In general, the performance of the model in simulating surface runoff volume in southern Louisiana is satisfactory.

Keywords: DRAINMOD model, watershed simulation, surface runoff simulation

INTRODUCTION

The purpose of this paper is to evaluate the applicability of the water management model, DRAINMOD, for flat agricultural field in southern Louisiana. DRAINMOD was developed at North Carolina State University, USA, for shallow water-table soils (Skaggs 1978). The model was developed for design and evaluation of multi-component water management systems which could include facilities for surface drainage, subsurface drainage, subirrigation and sprinkler irrigation (Skaggs 1978). The model is a computer simulation program which predicts, on an hour-by-hour, day-by-day basis, the water-table position, soil-water content, evapotranspiration, drainage, and surface runoff for given climatological data, soil and crop properties, and water management

1 The experimental work was carried out at Louisiana State University, USA.

system design parameters. The model is well documented by Skaggs (1978, 1980a and 1980b). Also, several reports of validation studies for the model using field data from different regions of USA have been reported by Skaggs (1977, 1980b and 1982), Skaggs *et al.* (1981), Gayle *et al.* (1985 and 1987), and Rogers *et al.* (1985).

MODEL DESCRIPTION

The model is based on a water balance for a thin section of soil of unit surface area which extends from the impermeable layer to the surface and is located midway between adjacent drains (*Fig. 1*). The water balance for a time increment of Δt may be expressed as

$$\Delta Va = D + ET + DS - F \tag{1}$$

where

ΔVa = the change in air volume (cm) in the section,
D = drainage (cm) from the section,
DS = deep seepage (cm),
ET = evapotranspiration (cm), and
F = infiltration (cm) entering the section.

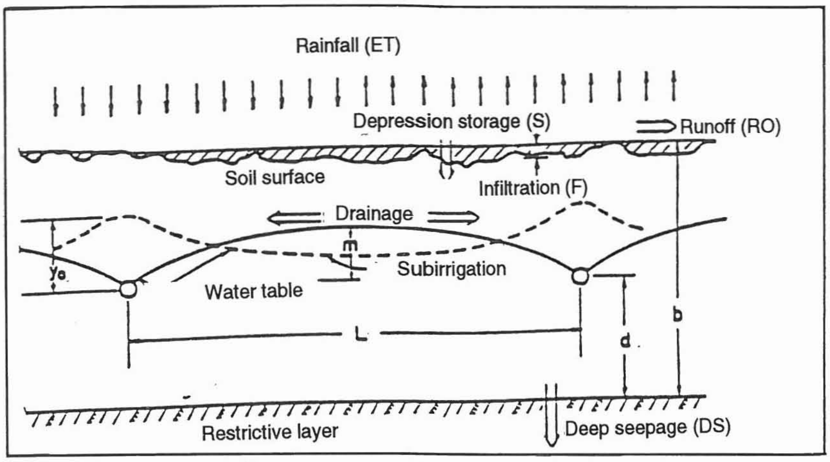

Fig. 1. Schematic drawing of the water management system for subsurface drains that may be used for drainage or subirrigation (After Skaggs 1980)

The amount of runoff and storage on the surface is computed from a water balance at the soil surface for each time increment which may be written as

$$P = F + \Delta S + RO \tag{2}$$

where

P = precipitation (cm),
F = infiltration (cm),
S = change in volume of water stored on the surface (cm), and
RO = runoff (cm).

The model is composed of a number of separate components which evaluate the various mechanisms of soil water movement and storage. The major components used in the model are: precipitation, infiltration, surface drainage, subsurface drainage, subirrigation, evapotranspiration, soil water distribution, and rooting depth. This paper provides a brief description of each of these components; however, for details one needs to refers to the DRAINMOD reference manual (Skaggs 1980a).

Precipitation

Precipitation records are one of the major inputs to the DRAINMOD model. Hourly rainfall records are used in the model to increase accuracy of predictions for infiltration, runoff, and surface storage.

Infiltration

Infiltration is described as the movement of water through the soil surface into the soil profile under the influence of gravity and capillarity. It is affected by soil factors such as hydraulic conductivity, initial water content, surface compaction, depth of profile, water table depth, plant factors such as extent of cover and depth of root zone, and rainfall factors such as intensity, duration, and time distribution. The model uses the Green and Ampt equation to characterize infiltration as

$$f = A/F + B \tag{3}$$

in which

$A = K_s * M_d * S_{av}$ and
$B = K_s$

where

f = infiltration rate (cm/h),
F = accumulative infiltration (cm),
K_s = hydraulic conductivity (cm/h),
M_d = the difference between final and initial volumetric water contents (cm^3/cm^3), and
S_{av} = effective suction at the wetting front (cm).

Surface Drainage

Surface drainage is characterized by the average depth of depression storage that must be filled before runoff can begin. When the surface storage depth as determined by equation 2 exceeds this value the additional excess is allotted to surface runoff.

Subsurface Drainage

The rate of subsurface water movement into drain tubes or ditches depends on the hydraulic conductivity of the soil, drain spacing and depth, effective drain radius, profile depth and water table elevation. The DRAINMOD model uses either Hooghoudt's or Kirkham's equation in calculating the flux, depending on whether the water table is at the surface and whether water is ponding or not. When the water table is below the surface, DRAINMOD uses Hooghoudt's steady state equation,

$$q = (8*K*d_e*m + 4*K*m^2)/L^2 \qquad (4)$$

where

q = flux in cm/h,
m = midpoint of water table height above the drain (cm),
K = the equivalent lateral hydraulic conductivity (cm/h),
d_e = the equivalent depth from the drains to the impermeable layer (cm), and
L = the distance between drains (cm).

When the water table completely inundates the surface with ponded water the Hooghoudt equation for predicting drainage flux is inadequate as it assumes a curved (elliptical) water table completely below the soil surface except at the midpoint where it may be coincident with the surface. Therefore, at inundation the drainage flux is calculated using an equation derived by Kirkham (1957),

$$G = 2 \ \ln\left[\frac{\tan(\pi(2b-r)/4h)}{\tan(\pi r/4h)}\right] + 2\sum_{m=1}^{\infty} \ \ln\left[\frac{\cosh(\pi m L/2h) + \cos(\pi r/2h)}{\cosh(\pi m L/2h) - \cos(\pi r/2h)} \cdot \frac{\cosh(\pi m L/2h) - \cos(\pi(2d-r)/2h)}{\cosh(\pi m L/2h) + \cos(\pi(2d-r)/2h)}\right] \qquad (5)$$

where

K_e = equivalent lateral hydraulic conductivity (cm/h),
h = actual depth of the profile (cm),
t = depth of the water on the surface (cm),
d = the actual depth from the drain to the impermeable layer (cm),
r = radius of drainage tube,

b = the depth from the surface to the drain (cm), and
L = the drain spacing (cm).

Evapotranspiration

The term evapotranspiration is used to describe the total process of water transfer into the atmosphere from vegetated land surfaces. Potential evapotranspiration is the evaporation from the extended surface of a short green crop which fully shades the ground, exerts little or negligible resistance to the flow of water, and is always well supplied with water (Rosenberg *et al.* 1983).

Potential evapotranspiration depends on climatological factors which include net radiation, temperature, humidity and wind velocity. Evapotranspiration can be estimated by using several methods such as Thornthwaite, Blaney-Criddle, Jensen-Haise, Penman, and Van Bavel. The method selected for use in the model was the method developed by Thornthwaite (1948),

$$PET = 1.6\ (10T/I)^{a} \qquad (6)$$

where

PET = total monthly potential evapotranspiration (cm),
T = the mean temperature of the month of measurement (°C),
I = heat index derived from the sum of 12 monthly index value, i
i = $(T/5)^{1.514}$, and
a = $6.75 \times 10^{-7} I^3 - 7.71 \times 10^{-5} I^2 + 1.79 \times 10^{-2} I + 0.49$

PREVIOUS RESEARCH ON DRAINMOD

Skaggs *et al.* (1981) evaluated the DRAINMOD model for North Central Ohio conditions by comparing predicted with measured drainage volumes for field plots with surface drainage alone, subsurface drainage alone and for combination plots with both surface and subsurface drainage. They found that predicted surface runoff and subsurface drainage volumes were in good agreement with measured values for all three drainage treatments.

Skaggs (1982) tested the performance of the DRAINMOD model for predicting water table elevations in North Carolina. He found that predicted and measured water table elevations were in satisfactory agreement with standard errors of estimate of the daily water table depths ranging from 7.5 to 19.6 cm. Based on the results of the study he concluded that the DRAINMOD model can be used to predict the effect of drainage system design on water table elevations.

Fouss *et al.* (1987) used the DRAINMOD model to simulate the subsurface drainage on a 4.4 ha watershed in the Lower Mississippi Valley. Predicted runoff, subsurface drain flow, and water table depth fluctuation compared closely with field observed values during a year when frequent rainfall events caused the water table to rise into the root zone (within 30 cm of the soil surface).

Rogers *et al.* (1985) evaluated the DRAINMOD model for the sandy soil conditions of South Central Florida by comparing predicted with measured drain outflows and water table elevations for 10 years of records. The model was modified to improve drain outflow. With the improved drain outflow prediction, annual and monthly evapotranspiration values were satisfactorily predicted.

Sanoja *et al.* (1990) used four years of field data to test the performance of the DRAINMOD model to predict the daily tile flows and water table elevations for Nicollet silt loam and Kenyon loam soils of Iowa. They found that predicted water-table depths and tile flow rates were in agreement with the measured values for all four years. The average deviation and standard error for the comparison of predicted and measured water-table depths ranged from 8.40 to 18.61 cm and 10.14 to 21.65 cm, respectively.

MATERIALS AND METHODS

Experimental Site Description

The Ben Hur research farm is located 5.5 km south of Louisiana State University, Baton Rouge, Louisiana. The farm is operated jointly by the Louisiana State University Agricultural Center and the United States Department of Agriculture. The soil, a Commerce clay loam, fine silty, mixed, non-acid, thermic aeric fluvaqent, has a saturated hydraulic conductivity of approximately 1 mm/h just below the plough depth and increases only slightly to a depth of about 0.6 m. Between 0.6 and 1.3 m depth there is a layer of approximately 0.3 m thickness with a saturated hydraulic conductivity of up to 80 mm/h (Rogers *et al.* 1985). More information about this soil may be obtained in Camp (1976) and Dance *et al.* (1968).

The field was installed in 1977 and partitioned into 4 plots (*Fig. 2*). Two plots (Plot E and Plot G) were 200 m long and 60 m wide. Plot E was surface-drained and contained subsurface drainage tubing (104 mm diameter) 1 m deep, spaced 20 m apart, and installed on a grade of 0.1%. Plot G was surface-drained only. Earth dikes at least 0.3 m high were constructed around the plots to define the plot boundaries and to ensure that runoff passed through an H-flume where it could be measured and sampled (Bengtson *et al.* 1985). The plots were not replicated. Rainfall was measured with a weighing-type recording rain gauge. Surface runoff was measured with an H-flume and FW-1 water stage recorder.

Silage corn was grown using conventional tillage, a sequence of disc and harrow, and planting up and down the slope in April. The plots were fertilized with 217, 38, and 76 kg/ha/year of nitrogen, phosphorus and potassium, respectively. Nitrogen was applied at 109 kg/ha at planting (disced in) and 108 kg/ha (side-dressed) 3 to 4 weeks after emergence. The corn was cultivated once each year in May for weed control, and was harvested for silage in July. The field was fallow the remainder of the year.

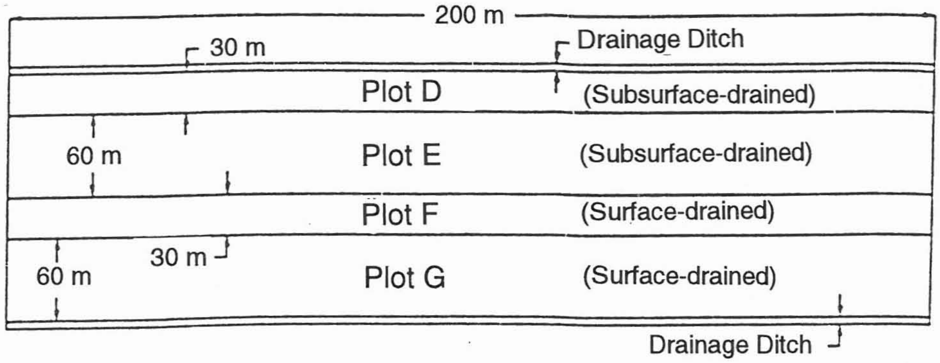

Fig. 2. Plan of Ben Hur research farm plots

Experimental Procedures

The DRAINMOD model was used to simulate the surface runoff volume from the subsurface-drained plot and the non-subsurface-drained plot. Seven years (from 1981 to 1987) of observed data were used to evaluate the performance of the model.

The model was evaluated by three methods. First, linear regression analysis was used to determine the closeness of observed and simulated values. The data were fitted to a simple linear regression model with the simulated data as the dependent variable and the observed data as the independent variable. The correlation coefficient, slope, and intercept were used to evaluate the capability of the model.

Secondly, a t-test was done on the intercept and slope of the relationship obtained from regression analysis between the observed and simulated data. The closer the slope of the regression line to unity, the better the model predicted the observed data. All statistical tests were carried out for a significance level of 0.05.

Thirdly, standard deviation of differences (STDD), absolute average difference (ADIF) and percentage error (PE) were computed comparing observed and predicted data. The following equations were used:

$$\text{STDD} = \sqrt{\frac{\sum (\text{obs} - \text{pred})^2}{n}} \tag{7}$$

$$\text{ADIF} = \frac{\sum |\text{obs} - \text{pred}|}{n} \tag{8}$$

$$\text{PE} = \left(\frac{\text{pred} - \text{obs}}{\text{obs}}\right) \times 100 \tag{9}$$

where

obs = observed value,
pred = simulated value, and
n = number of observations.

The standard deviation of differences is a measure of the dispersion of the simulated data from the observed data and is expressed in the units of the observed data (Chang *et al.* 1983). The absolute difference is simply the absolute difference between the observed and the simulated data averaged over the number of observations. The percentage error is a measure of the difference between the observed and simulated data relative to the observed data, and is expressed as a percentage.

MODEL INPUT PARAMETERS

This section will provide a brief description of the various sections of the input data. Measured data were made available by Dr. Richard Bengtson of the Agricultural Engineering Department and Dr. James Fouss of the USDA-ARS, Louisiana State University, USA.

Input to the DRAINMOD model can be divided into two groups, input data and input parameters. The input data are of two types, climatological and crop data. The input parameters can be divided into soil properties and drainage system parameters.

Climatological Data

Precipitation and daily maximum and minimum air temperature were recorded at the experimental site. Precipitation was recorded in a breakpoint format. However, the model requires that the precipitation is entered in hourly values. Rainfall was recorded in hundredths of inches which the program converts to centimetres before using. The monthly and annual rainfall data values are shown in Table 1. The 28-year average annual rainfall for the Ben Hur research farm is 146 ± 29 cm (Fouss *et al.* 1987). Daily maximum and minimum air temperatures are used by the model to estimate potential evapotranspiration by the Thornthwaite method.

Crop Data

The crop data required by the model include the effective root depth as a function of time and the growing season. It is used in the model to define the zone from which water can be removed as necessary to supply evapotranspiration demands. The rooting depth function is read as a table of effective rooting depth versus Julian date. The rooting depth for days other than those listed in the table is obtained by interpolation. The rooting depth used in this study is shown in Table 2.

TABLE 1
Monthly and annual rainfall, Ben Hur research farm, Louisiana

Month	Monthly rainfall (cm) for years						
	1981	1982	1983	1984	1985	1986	1987
Jan	2.51	8.89	11.07	8.28	12.09	4.29	20.07
Feb	20.65	14.07	13.39	16.29	11.66	13.69	19.84
Mar	5.72	7.14	11.30	3.99	11.91	6.32	13.00
Apr	2.82	12.34	21.69	3.56	11.94	5.97	2.49
May	11.18	4.29	17.91	11.10	6.63	7.57	17.07
Jun	22.00	9.75	24.43	9.53	8.23	14.33	31.75
Jul	15.72	3.58	8.28	5.61	7.02	12.78	12.27
Aug	5.87	17.93	28.09	12.73	14.81	10.36	27.36
Sep	8.15	8.20	15.21	9.04	21.54	4.04	3.61
Oct	4.22	10.24	2.69	21.95	22.23	10.06	2.36
Nov	4.34	9.78	11.81	5.56	3.02	31.01	11.18
Dec	13.77	36.25	15.11	8.43	11.33	15.04	6.27
G.S.*	57.59	47.89	100.40	42.53	48.63	51.01	90.94
Total	116.94	142.47	181.00	116.05	142.40	135.46	167.26

*G.S. = growing season from April 1 to August 31 (for corn silage crop)
Note: 28-year average: G.S. 68 ± 17 cm
annual 146 ± 29 cm

TABLE 2
Effective rooting depth (cm) as a function of time for corn
(after Skaggs *et al.* 1981)

Month	Day	Root depth
1	1	3.0
3	31	3.0
4	18	10.0
5	1	15.0
5	5	25.0
6	4	30.0
7	2	30.0
9	11	30.0
9	21	10.0
10	19	3.0
12	31	3.0

Soil Properties

The soil properties consist of: soil water characteristics, drained volume as the function of water-table depth, upward flux, hydraulic conductivity, and infiltration. The soil water characteristics are shown in Table 3. Both the drained volume versus water table depth and also the steady upward flux versus water table depth are given in Table 4. The saturated hydraulic conductivity and parameters for the Green-Ampt infiltration equation are shown in Table 5 and Table 6, respectively.

TABLE 3
Soil-water characteristics (Commerce clay loam soil)

Pressure head (cm)	Water content (cm^3/cm^3)
-0	0.458
-10	0.452
-20	0.440
-30	0.431
-40	0.422
-50	0.412
-60	0.402
-70	0.397
-80	0.392
-100	0.381
-120	0.374
-160	0.359
-200	0.352
-500	0.324

TABLE 4
Drained volume and steady-state upward flux vs. water table depth (Commerce clay loam soil)

Water table depth (cm)	Drained volume (cm)	Steady-state upward flux (cm/h)
0	0.00	1.000
10	0.10	0.264
20	0.39	0.072
30	0.65	0.030
40	0.90	0.019
50	1.10	0.012
60	1.40	0.008
70	1.80	0.006
80	2.20	0.004
100	3.00	0.000
120	4.50	0.000
160	8.00	0.000
200	12.20	0.000
500	50.00	0.000

TABLE 5
Saturated hydraulic conductivity vs. soil depth
(Commerce clay loam soil)

Depth in soil (cm)	Sat. hydr. cond. (K) (cm/h)
0.0 to 50.0	1.2
50.0 to 120.0	4.0
120.0 to 141.5	0.1

TABLE 6
Parameters for the Green-Ampt infiltration equation for
various water table depths at the start of rainfall
(Commerce clay loam soil)

Initial depth of water table (cm)	A ($A=K_sMS_{av}$) (cm^2/h)	B ($B=K_s$) (cm/h)
0	0.0	0.4
30	0.4	0.4
60	0.8	0.4
120	1.12	0.4
150	1.76	0.4
500	1.76	0.4
500	1.76	0.4

Drainage System Parameters

Input data required to describe the design of the drainage system are summarized in Table 7. These data are used in combination with soil property data to compute surface runoff, drainage flow, evapotranspiration, water table depth, etc., in the drainage system simulation process.

For details on input data, one needs to refer to chapter 4 of the DRAINMOD reference manual (Skaggs 1978).

SIMULATION RESULTS AND DISCUSSION

Subsurface-drained Plot

The annual values of observed and simulated surface runoff volume are shown in Table 8. The model simulated accurately the total surface runoff for the years 1981 and 1987, overestimated the total surface runoff for the years 1982, 1983, 1986, and underestimated for the years 1984 and 1985.

TABLE 7
Summary of drainage system input parameters, Ben Hur research farm, Louisiana

Parameter	Variable name	Value
Drain spacing	SDRAIN	2000, 9144 cm *
Drain depth	DDRAIN	100 cm
Equivalent depth to impermeable layer	HDRAIN	41, 48 cm *
Equivalent profile depth	DEPTH	141, 148 cm*
Maximum depth of surface storage	STMAX	0.25 cm
Drain radius	**	10 cm
Effective drain radius	**	0.5 cm

* for subsurface-drained plot and non-subsurface-drained plot, respectively.
** these variables are not inputs to DRAINMOD but are used to calculate HDRAIN.

TABLE 8
Observed and simulated annual surface runoff of subsurface-drained plot

Year	Observed (cm)	Simulated (cm)	%Error
1981	19.17	19.37	1.0
1982	24.70	34.87	41.2
1983	46.63	53.08	13.8
1984	14.98	13.22	-11.8
1985	33.70	32.39	-3.9
1986	28.89	30.26	4.7
1987	42.26	43.34	2.5
Total	210.33	226.53	7.7

The observed and simulated surface runoff volumes accumulated by months for the 7-year period are shown in *Fig. 3*. Over the first 23 months of the study the accumulated simulated values were very close to the observed values (*Fig. 3*). The overestimation of the surface runoff prediction was due to several reasons. The growing season in 1982 was drier than normal. The model overpredicted the surface runoff volume due to underpredicting the evapotranspiration. During this period the crop usually has a longer root system to search for water at deeper depths. It was also reported that in 1982 Johnson grass was predominant after the corn silage was harvested. In December 1982 the model overestimated the surface runoff volume by 33.2%. The amount of the rainfall recorded for this plot in that month was 36.25 cm, 139% higher than the average December rainfall of 15.17 cm. It was the highest recorded monthly rainfall for the 7-year period.

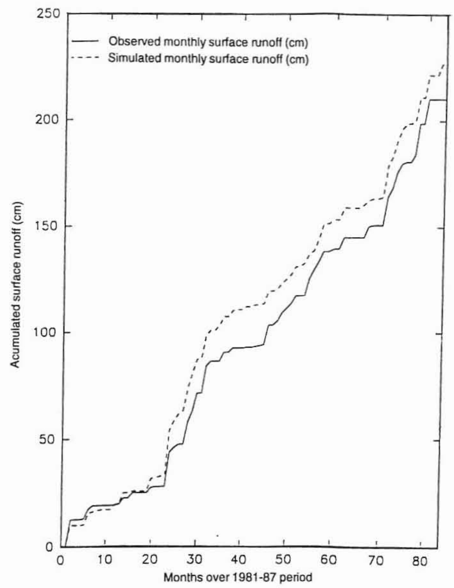

Fig. 3. Observed and simulated surface runoff volume accumulated by months of subsurface-drained plot

Regression analysis gave the following relationship between monthly simulated and observed surface runoff:

$$Q_{SM} = 0.42 + 0.91\ Q_{OM} \qquad (10)$$
$$r = 0.92$$

where

Q_{SM} = simulated monthly surface runoff (cm)
Q_{OM} = observed monthly surface runoff (cm), and
r = correlation coefficient

The relationship between observed and simulated monthly surface runoff during this period is shown in *Fig. 4.* Numerous data points are clustered near the 0:0 coordinate. The regression line fitted closer to the 1:1 line at low monthly surface runoff than it did at high value of surface runoff. The correlation coefficient is high, indicating a good straight line relationship between simulated and observed monthly surface runoff. The ANOVA test demonstrated that a significant linear relationship exists between simulated and observed monthly surface runoff. A t-test was done on the intercept and slope of the relationship shown by equation 10. It was found that the slope of the regression line was not statistically different from 1.0. However, the intercept was statistically different from zero. The total simulated surface runoff was 7.7% greater than the total observed surface runoff.

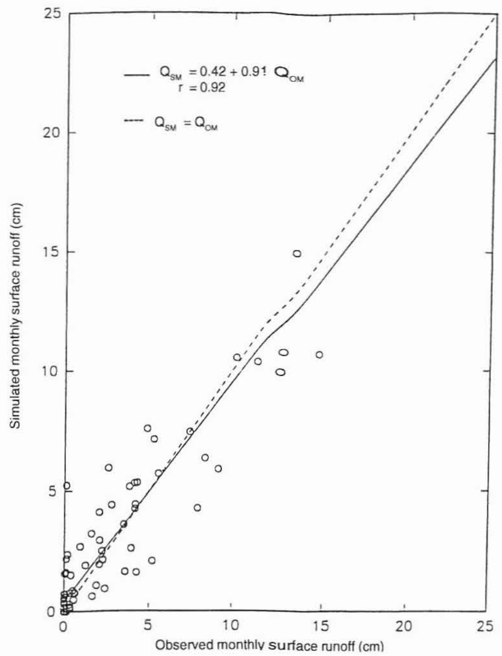

Fig. 4. Relationship between simulated and observed monthly surface runoff of subsurface-drained plot

Non-subsurface-drained Plot

The annual values of observed and simulated surface runoff volume are shown in Table 9. The model overestimated the total surface runoff for all years. The observed and simulated surface runoff volume accumulated by months is shown in *Fig. 5*. As in subsurface-drained plot, the model seriously overestimated the surface runoff in December, 1982.

TABLE 9
Observed and simulated annual surface runoff of non-subsurface-drained plot

Year	Observed (cm)	Simulated (cm)	%Error
1981	25.79	34.74	34.7
1982	36.82	55.55	50.9
1983	77.80	90.72	16.6
1984	20.81	35.96	72.8
1985	45.72	55.42	21.2
1986	46.96	49.93	6.3
1987	67.46	79.82	18.3
Total	321.36	402.14	25.1

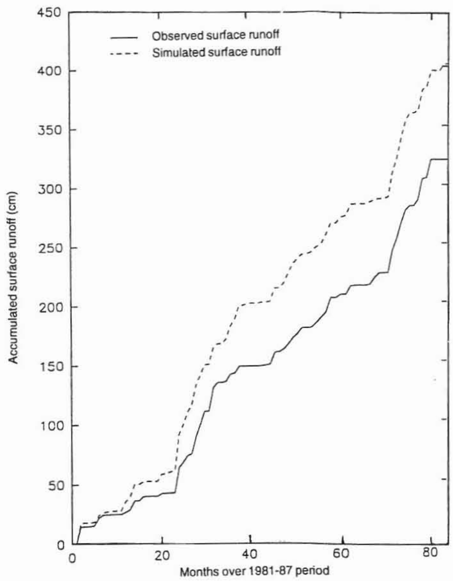

Fig. 5. Observed and simulated surface runoff volume accumulated by months of non-subsurface-drained plot

Regression analysis gave the following relationship between monthly simulated and observed surface runoff:

$$Q_{SM} = 0.31 + 1.07\, Q_{OM} \qquad (11)$$
$$r = 0.67$$

The relationship between observed and simulated annual surface runoff is shown in *Fig. 6.* The ANOVA test demonstrated that a significant linear relationship existed between simulated and observed monthly surface runoff. The slope of the regression line was not statistically different from 1.0. However, the intercept was statistically different from zero. The total simulated surface runoff was 25.1% greater than the total observed surface runoff.

The standard deviation of differences (STDD), which measure the dispersion of the predicted data from the observed data, and the absolute average differences (ADIF) between the observed and simulated data were computed for the model simulations of both plots and are presented in Table 10. The values for the subsurface-drained plot are smaller then those obtained from the non-subsurface-drained plot.

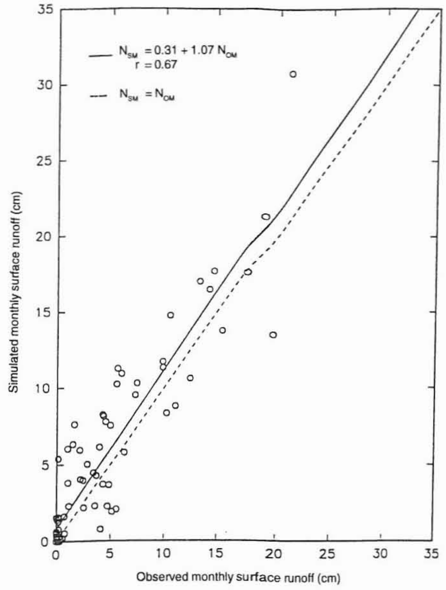

Fig. 6. Relationship between simulated and observed monthly surface runoff of non-subsurface-drained plot.

TABLE 10
Error statistics computed to evaluate DRAINMOD-CREAMS model predictions on surface runoff

Statistics	Surface Runoff (cm)	
	Subsurface	Non-Subsurface
STDD[1]	1.54	2.56
ADIF[2]	0.96	1.73

[1] Standard deviation of differences.
[2] Absolute average difference between the observed and the simulated data.

CONCLUSION

The DRAINMOD model overestimated the surface runoff volume by 7.7% and 25.1% from the subsurface-drained plot and the non-subsurface-drained plot, respectively. The standard deviation of differences and average absolute difference comparing the observed and simulated values are smaller in the subsurface-drained plot. The DRAINMOD model predicted the surface runoff more accurately in the subsurface-drained plot than the non-subsurface-drained plot. Both predictions were subject to potential errors in predicting evapotranspiration. In general, the performance of the DRAINMOD model in simulating the surface runoff in southern Louisiana is satisfactory.

Recommendations for Future Research

The DRAINMOD model should be modified to accept several sets of rooting depths depending on the amount of rainfall during the growing season. This model modification could improve the prediction of the surface runoff volume during dry seasons, because removal of water from the soil profile would be increased by simulated evaporation of the deeper-rooted plants.

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