INFILTRATION AND RUNOFF SIMULATION ON A PLANE

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ABSTRACT

A program which computes infiltration and the overland flow hydrograph on a single, homogeneous plane is described. Infiltration is computed by the Green and Ampt equation and the hydrograph is computed by a semi-analytical method of characteristics solution of the kinematic wave model for overland flow. Default parameter estimation values are supplied by the program for both the infiltration and hydrograph models. Use of the model as a tool for parameter selection is illustrated with rangeland rainfall simulator data. **KEYWORDS.** Runoff, Infiltration.

INTRODUCTION

As a part of the USDA Water Erosion Prediction Project (WEPP) we have written a program called IRS (Infiltration and Runoff Simulator) to compute infiltration and rainfall excess on a plane and the overland flow hydrograph at the end of a plane. This program is intended to serve three main purposes: 1) to have a source code to modify and incorporate into the WEPP Representative Profile model; 2) to have an infiltration-runoff-hydrograph program to serve as a benchmark to use in WEPP model verification and validation studies; and 3) to have a means to analyze rainfall simulator data. Program IRS calculates infiltration by the Green-Ampt equation for an arbitrary rainfall rate, rainfall excess as the difference between rainfall and infiltration, and the overland flow hydrograph at the end of a single plane by solving the kinematic wave equation using the method of characteristics.

This article presents an overview of the IRS program, special characteristics of the solutions generated by a semi-analytical solution of the kinematic wave model, parameter estimation contained within the program, and an application of the program to rainfall simulator data parameter selection.

OVERVIEW

Dynamic infiltration-hydrograph models for overland flow consist of an infiltration function which computes the infiltration rate as it varies with time from an unsteady rainfall input and a routing function which transforms rainfall excess into flow depths on a flow surface. The choice of the infiltration function is somewhat arbitrary, but the routing function is generally some form of the St. Vennant shallow water equations. One such form, the kinematic wave model, has been shown (Woolhiser and Ligget, 1967) to be a valid approximation for most overland flow cases. For the IRS program we have chosen the Green and Ampt equation and a semi-analytical solution of the kinematic wave equation as the infiltration and routing functions respectively. The choice of the two models was motivated by the existence of Green and Ampt parameter values for a wide range of soils (Rawls et al., 1982), the potential that the parameter values could be adjusted to account for soil, vegetation, and management temporal variability, and because the execution time is rapid.

KINEMATIC WAVE MODEL

The kinematic equations for flow on a plane are the continuity equation:

$$\frac{\partial h}{\partial t} + \frac{\partial q}{\partial x} = v \qquad (1)$$

and a depth-discharge relationship:

$$q = \alpha\, h^{m} \qquad (2)$$

where

h = depth of flow (L),
q = discharge per unit width of the plane (L^3/L-T),
v = rainfall excess rate (L/T),
α = depth-discharge coefficient (i.e., Chezy or Manning),
m = depth-discharge exponent ($m = 3/2$ for Chezy and $m = 5/3$ for the Manning equation),
t = time (T), and
x = distance from top of plane (L).

If the Chezy relationship is used, $\alpha = C\, S^{1/2}$ where C = Chezy coefficient ($L^{1/2}$/T) and S = slope of the plane (L/L). If the Manning relationship is used, $\alpha = C\, S^{1/2}/n$ where n = Manning coefficient (T/$L^{1/3}$). Note that L denotes dimensions of length and T denotes dimensions of time. The initial and boundary conditions are:

$$h(x,0) = h(0,t) = 0. \qquad (3)$$

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Analytic (Henderson and Wooding, 1964) and semi-analytic (Harley et al., 1970; Eggert, 1987) solutions for equations 1 and 2 given equation 3 have been developed using the method of characteristics. The method involves rewriting equations 1 and 2 as simple ordinary differential equations in terms of the flow depth at a distance on the plane. These equations are termed the characteristic equations. The equations for depth and distance along a characteristic c(t,x) at a given time are (see Eagleson (1970) for a derivation of the characteristic equations):

$$\frac{dh}{dt} = v(t). \tag{4}$$

$$c(t,x) = \frac{dx}{dt} = \alpha\, m\, h(t)^{m-1} \tag{5}$$

The characteristic (eq. 5) defines a locus of points in the time-space plane on which the flow depth is computed by equation 4. If equations 4 and 5 are integrated we get:

$$h = h_1 + \int_{t_1}^{t_2} v(w)\, dw \tag{6}$$

$$x = x_1 + \alpha\, m \int_{t_1}^{t_2} h(w)^{m-1}\, dw \tag{7}$$

where x_1 is the distance down the plane where the depth is equal to h_1 (L), h_1 is depth at time t_1, t_1 and t_2 are limits of integration (T), and w is the dummy variable of integration.

Although an analytical solution of the kinematic wave model can be obtained by assuming a constant rainfall excess (Henderson and Wooding, 1964), a more general semi-analytical solution can be obtained by defining rainfall excess as a step function. Following Harley et al. (1970), we define rainfall excess as:

$$\begin{array}{lll} v(t) = r(t) - f(t) & \text{for} & r(t) > f(t) \\ v(t) = 0 & \text{otherwise} & \end{array} \tag{8}$$

where the functions v(t), r(t), and f(t) are the rates (L/T) at time t for rainfall excess, rainfall, and infiltration, respectively. Note in equation 8, rainfall excess is only computed when the rainfall rate exceeds the infiltration rate. The advantage of equation 8 is that infiltration may be computed independent of the flow computations. The disadvantage is that infiltration is not computed during the time when water is still flowing on the plane and the rainfall rate is less than the infiltration capacity or rainfall ceases. The result is that the volume of runoff during the recession phase of the hydrograph is always over estimated by equation 8.

SOLUTION BY THE METHOD OF CHARACTERISTICS

The general solution procedure is to solve equation 6 for the depth of flow at a time and then solve equation 7 for the distance from the top of the plane that the depth occurs. Because we are interested in the hydrograph at the end of the plane, the distance solved for in equation 7 is the length of the plane. The discharge rate is computed by solving equation 2 given the depth found by equation 6. Detailed solutions of the kinematic wave model for overland flow by the method of characteristics for the case of unsteady rainfall excess have been well described by Harley et al. (1970) and Eggert (1987). Therefore, only two properties of the solution will be discussed herein.

Lane et al. (1988) identified four regions in the t-x plane and described the flow characteristics of each region (see fig. 1 for a definition sketch of the characteristic plane): zone A, flow establishment; zone B, flow established; zone C, partial equilibrium; and zone D, recession. Because rainfall excess is defined by equation 8, the hydrograph generated by equations 6 and 7 exhibit two physically unrealistic properties, partial equilibrium or flat topped hydrographs and infinite runoff duration. Partial equilibrium hydrographs occur when the rainfall excess ends before the c(0,0) characteristic reaches the end of the plane. The c(0,0) characteristic is that which originates at the top of the plane at the start of rainfall excess. It is also termed the equilibrium characteristic because it denotes the time at which the plane reaches steady state flow under constant rainfall excess. In terms of the t-x plane, partial equilibrium occurs when the solution switches from zone A to zone C. The solution of equations 6 and 7 in zone C are:

$$h(t) = \int_0^{t_*} v(w)\, dw \equiv h_* \tag{9}$$

$$x = x_* + \alpha\, m\, h_*^{m-1}(t - t_*) \tag{10}$$

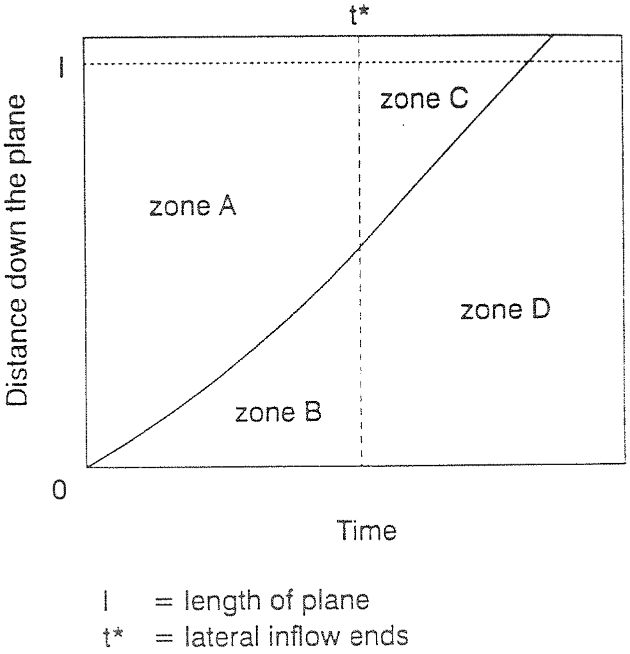


Figure 1–The four flow zones in the t-x plane.

where t_* is time rainfall excess ends (T), h_* is the depth on the characteristic in zone C (L), and x_* represents the location on the plane where the characteristic switches from zone A to zone C (L). Note that by equation 9, the flow depth is a constant and that by equation 10, the characteristic is a straight line while the solution is in zone C. Referring to figure 2, during the time from t_* to t_{c0}, the time c(0,0) reaches the end of the plane, the flow depth at the end of the plane is constant, and by equation 2, the hydrograph discharge is constant. Partial equilibrium is physically unrealistic on an infiltrating surface because at the time the infiltration rate is greater than the rainfall rate or rainfall ceases, infiltration continues as long as water is ponded on the surface. Thus the runoff flow depth immediately begins to decrease. The definition of rainfall excess used in IRS (eq. 8), however, does not allow for infiltration after rainfall ceases, so partial equilibrium hydrographs occur. Indeed, for most practical applications of IRS, partial equilibrium will not occur. It is difficult to generalize if a particular application will result in partial equilibrium, if the rainfall excess is an arbitrary function as it is when computed with the Green and Ampt equation. However, for the case of constant rainfall excess, the time to kinematic equilibrium, t_e (T), which is the time that c(0,0) reaches the end of the plane is:

$$t_e = \left(\frac{l}{\alpha v^{m-1}}\right)^{1/m} \tag{11}$$

where l represents length of the plane (L). As can be seen from equation 11, the longer the plane, the smaller the rainfall excess rate, or the rougher the surface, the longer it takes c(0,0) to reach the end of the plane. For example, on a rainfall simulator plot with a length of 10.7 m, a slope of 5%, a Chezy roughness coefficient of 2, and a rainfall excess rate of 10 mm/h, the time to kinematic equilibrium is 9.8 min. Thus, if the duration of rainfall excess is less than 9.8 min, the hydrograph will be in partial equilibrium. If the duration is greater partial equilibrium will not occur.

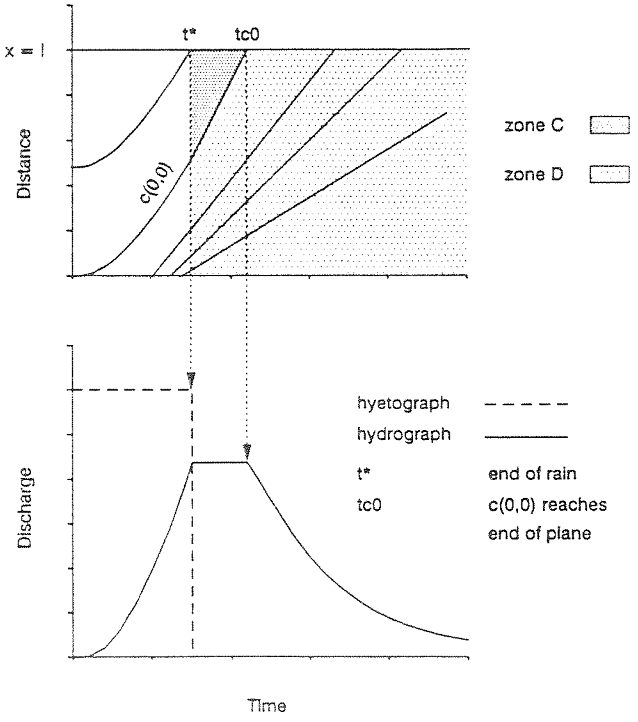


Figure 2–Characteristics in zone C and zone D.

The solution in zone D is the recession of the hydrograph with the water surface elevation decreasing everywhere on the plane. The solution of equations 6 and 7 in zone D are:

$$h(t) = \int_{t_0}^{t_*} v(w)\,dw \equiv h_r \tag{12}$$

$$l = x_* + \alpha\, m\, h_r^{m-1} (t - t_*) \tag{13}$$

where t_0 is the time the characteristic originated at the top of the plane (T), h_r is depth on the characteristic in zone D (L), and x_* is the location on the plane where the solution switches from zone A or C to zone D (L). By equation 12, the depth is constant on a characteristic within zone D and, by equation 13, time approaches infinity as the depth approaches zero.

INFILTRATION

Infiltration in IRS is calculated using a solution of the Green-Ampt equation for an arbitrary rainfall intensity pattern presented by Chu (1978). The form of the Green and Ampt equation for cumulative infiltration depth can be written as:

$$K_e t = F - N_s ln\left(1 + \frac{F}{N_s}\right) \tag{14}$$

where K_e is the effective saturated conductivity (L/T), F is the cumulative infiltration (L), and N_s is the effective matric potential (L). The effective matric potential is computed as:

$$N_s = (\eta_e - \theta_v)\,\psi \tag{15}$$

where η_e is effective porosity (L/L), θ_v is volumetric water content (L/L), and ψ represents average matric potential across the wetting front (L). The effective porosity is computed as 0.9 η_T (Mualem, 1974) where η_T is the total porosity computed from the bulk density. The instantaneous infiltration rate, f (L/T), is computed as:

$$f = K_e\left(1 + \frac{N_s}{F}\right) \tag{16}$$

Before time to ponding, the infiltration rate is equal to the rainfall rate and the cumulative infiltration is equal to the cumulative rainfall. At the time that ponding occurs, the infiltration rate is equal to the rainfall rate. Chu (1978) rearranged equation 16 to obtain a ponding indicator, C_u, as:

$$C_u = R - V - \frac{K_e N_s}{r - K_e} \qquad (17)$$

where R is the cumulative rainfall (L), V is the cumulative rainfall excess (L), and r is the rainfall rate (L/T). If rainfall is a step function, then ponding occurs within the rainfall interval where C_u becomes positive. Rainfall excess is included in equation 17 for the case of multiple ponding times. The time to ponding, t_p, is computed as:

$$t_p = \left(\frac{K_e N_s}{r - K_e} - R + V \right) \frac{1}{r} + t \qquad (18)$$

After time to ponding, equation 14 is solved for F using a Newton Raphson iteration. The average infiltration rate for a time interval, f_{i-1} (L/T), is computed as:

$$f_{i-1} = \frac{F_i - F_{i-1}}{t_i - t_{i-1}} \qquad (19)$$

where i indicates the current time and i – 1 indicates the previous time.

INPUT

Although dynamic infiltration equations and the kinematic wave model have been used previously in models (for examples see CREAMS hydrology option 2, Smith and Williams, 1980; KINEROS, Woolhiser et al., 1990) the issue of parameter estimation remains the most difficult problem in the application of any time based infiltration-runoff model. Imbedded within the IRS program are parameter estimation routines which, while not extensively validated, aid the user in selecting the relevant parameter values. USDA agencies such as the Agricultural Research Service, Soil Conservation Service, and Forest Service are presently in the process of extending the data base used to estimate the Green and Ampt parameters for a wide range of soils, vegetation, and management practices through their collective efforts in WEPP. Thus, the parameter estimation procedures described below will change as the results of this research become available.

RAINFALL

Both constant and unsteady rainfall intensities with or without periods of zero rainfall can be input. It should be noted that because IRS is intended to be used as a single event model, redistribution of soil moisture between infiltration events is not computed. Therefore, if the interval of zero rainfall for an intermittent event is greater than one hour, it is recommended that the rainfall event be divided into separate events and the initial soil moisture conditions for the subsequent events be computed by the user.

INFILTRATION PARAMETERS

The Green and Ampt equation has four parameters to be estimated, K_e, η_e, θ_v, and ψ. Imbedded within IRS are default base line values (Table 1) for K_s, η_T, and ψ based on Rawls et al. (1982) for each of the 12 soil textures. The K_s values listed in Table 1 are equal to the K_s reported by Rawls et al. (1982) divided by two. The division by two is an approximation to account for the effects of crusting on the effective saturated conductivity. Program IRS does include several adjustments to compute effective values from the base line values. The K_s values listed in Table 1 can be adjusted to account for the effects of ground surface and vegetative canopy cover. This adjustment is based on an unpublished analysis of rainfall simulator data on desert brush dominated sites in Arizona and Nevada and has the form:

$$K_e = K_s\, e^{(0.009SC + 0.0105CC)} \qquad (20)$$

where SC is the surface cover (%), and CC is canopy cover (%). The surface cover is defined as rock fragments > 5 mm in diameter, vegetation litter, and vegetation mass (exposed root crowns) on the ground surface. The canopy cover is defined as any vegetation material (leaves, branches) which are above the ground surface. The effective matric potential, N_s, is computed by the program with equation 15 using the default matric potential from Table 1. As was noted before, soil moisture redistribution due to upward or downward fluxes between events in not computed.

HYDROGRAPH PARAMETERS

If the Chezy roughness relationship is chosen, the user has the option to input a value of C, choose a C derived from unpublished rainfall simulator data, or have the program calculate C based on rill roughness and cover relationships. For the second option, the values for C for a bare, clipped and vegetated surface are 9.2, 3.3, and 2.5, respectively. For the third option, C is calculated as:

$$C = \left(\frac{8g}{f} \right)^{0.5} \qquad (21)$$

where g is acceleration due to gravity (m/s^2), and f is the Darcy-Weisbach friction factor. The latter is computed as (Foster et al., 1980):

Table 1. The IRS default values for K_S, ψ, and η_T

Texture	K_S (mm / h)	ψ (mm)	η_T (mm / mm)
Sand	90.0	49	0.40
Loamy sand	30.0	63	0.40
Sandy loam	11.0	90	0.41
Loam	6.5	110	0.43
Silt loam	3.4	173	0.49
Silt	2.5	190	0.42
Silty clay loam	1.5	214	0.35
Clay loam	1.0	210	0.31
Silty clay loam	0.9	253	0.43
Sandy clay	0.6	260	0.32
Silty clay	0.5	288	0.42
Clay	0.4	310	0.39

$$f = 1.0 + 13.0\,(1.0 - e^{-0.0773rr}) + 18.52\left(\frac{SC}{100}\right)^{1.267} \quad (22)$$

where rr is random roughness (mm). If the Manning roughness relationship is chosen, the user has the option to enter a value for n or choose from tabular values (Table 2) developed from rainfall simulator data by Engman (1989).

EXAMPLE OF APPLICATION

The objectives of this section are to evaluate the compatibility of IRS with the rangeland rainfall simulator design and illustrate the use of IRS in parameter selection for rainfall simulator plots. It is not intended to be an exhaustive evaluation of the rangeland rainfall simulator data nor of parameter identification or estimation techniques.

RAINFALL SIMULATOR DATA

As part of WEPP, rainfall simulator experiments were conducted on rangeland sites in the western United States. The major objective of the experiment was to determine erodibility parameters for a range of soil textural classes. A secondary objective was to determine how infiltration characteristics are affected by canopy and ground cover characteristics on the plots. The experimental design consisted of applying water using a rotating boom rainfall simulator on 3.05 × 10.7 m plots for three separate runs; dry, wet, and very wet. For the dry run, water was applied at an intensity of approximately 60 mm/h for 45 to 60 min. The wet run was made 24 hours later using the same intensity for 23 to 30 minutes. The very wet run was made 30 min after the wet run using two intensities, 60 mm/h and 120 mm/h. Each intensity of the very wet run was applied until the runoff hydrograph appeared to reach steady state. A full description of the experimental design and physical characteristics of the sites are given by Simanton et al. (1991). Plot treatments on most of the rangeland sites included natural, clipped, and bare. For the natural treatment, the plot was left undisturbed. The clipped treatment consisted of removing all canopy cover to a 20 mm height and removing the clipped material from the plot. The bare treatment consisted of removing all canopy and ground cover and removing approximately 1 cm of soil in order to remove root crowns. Each treatment was replicated two times at each site. Data collected needed as input to IRS included rainfall intensity, the runoff hydrograph at the end of the plot, plot canopy and ground cover, soil texture, soil bulk density, and soil moisture before the dry and wet runs.

Table 2. Manning's n values for rainfall simulator plots (from Engman, 1989)

Cover / Treatment	Residue (T / ac)	Manning's n ($s/m^{1/3}$)
Bare / fallow	< 1.4	0.045
Grass / sod		0.530
Chisel	< 1.4	0.075
	1.4 – 1	0.180
	1 – 3	0.340
	>3	0.450
Range / natural		0.130
Disk / harrow	< 1.4	0.078
	1.4 – 1	0.170
	1 – 3	0.270
	>3	0.310
Notill	< 1.4	0.053
	1.4 – 1	0.083
	1 – 3	0.350
Plow (fall)	< 1.4	0.055
Coulter	< 1.4	0.110

The bare and natural treatment plots from four rangeland sites were chosen to be used in this analysis: A1, Walnut Gulch, Arizona; D1 and D2, Chickasha, Oklahoma; and H2, Cottonwood, South Dakota. General plot characteristics for the four sites are listed in Table 3. The cover values listed in Table 3 are for the natural treatment plots. The bare treatment plots had zero canopy and ground cover at the time of the experiment.

PARAMETER SELECTION

There are two common methods of selecting parameters for hydrologic models, parameter identification, and parameter estimation. Parameter identification is an optimization process in which the identified parameter is adjusted until the simulated results match observed data. It is a useful tool to evaluate the effectiveness of the model structure in simulating the desired process when both the input and output data are available. Parameter estimation is choosing parameter values based on some criteria other than directly from the data of the process which is being simulated. Estimation is necessary to apply a model to situations where there are no data to identify parameters. In this section we describe how two parameter identification procedures and the estimation procedure imbedded in the IRS program are used to select default parameter values for WEPP rangeland rainfall simulator experimental plots.

For the three parameter selection procedures, ψ was obtained from Table 1 based on the soil textural class of the plot, η_e was computed from the measured dry bulk density, θ_v was computed from gravimetric measurements before the dry and wet runs, and SC and CC were computed from point frame measurements on the plots.

For the two parameter identification procedures, Chezy C was computed using the solution of the kinematic wave equation at equilibrium to calculate the amount of water present on the plane just before the end of the very wet run. Using the solution of the kinematic wave model

Table 3. Site characteristics of the rainfall simulator experiment

Site	Soil	Vegetation	Slope* m / m	Cover* % Canopy	Cover* % Ground
A1 Walnut Gulch, AZ	gravely sandy loam	desert shrub	11.0	32	82
D1 Chickasha, OK	loam	native tallgrass prairie	5.0	64	89
D2 Chickasha, OK	vf. sandy loam	reverted tallgrass prairie	4.5	33	56
H2 Cottonwood, SD	clay	mixed grass prairie	11.5	36	79

* Average for the site (natural plots).

given a constant rainfall excess, the equilibrium discharge, q_e ($L^3/L{-}T$), is:

$$q_e = v\,l \tag{23}$$

Combining equations 2 and 23, integrating the depth with respect to distance, and solving for Chezy C gives:

$$C = \left(\frac{m}{m+1}\,\frac{1}{S_t}\right)^m v\, l^{m+1}\, S^{-0.5} \tag{24}$$

where S_t, is the detention storage (L^2/T) and is computed as:

$$S_t = \int_0^l h(w)\,dw. \tag{25}$$

During most conditions on infiltrating surfaces, rainfall excess is never exactly constant. However, at the end of the very wet run, the hydrograph is near steady state. It is reasonable to assume that the unit area rainfall excess rate, v_{vw}, is constant and equal to the unit area runoff discharge rate, q_{vw}. The discharge per unit width of the plot is then:

$$q = v_{vw}\, l = q_{vw}\, l. \tag{26}$$

The detention storage can be estimated from the rainfall simulator data as:

$$S_t = Q_r\, l \tag{27}$$

where Q_r is the recession runoff depth volume (L). Equation 24 can then be rewritten in terms of the rainfall simulator data as:

$$C = \left(\frac{m}{m+1}\,\frac{1}{Q_r\, l}\right)^m q_{vw}\, l^{m+1}\, S^{-0.5} \tag{28}$$

Infiltration after rainfall ceased was assumed to be negligible in relation to S_t.

The two parameter identification procedures involved estimating the effective saturated conductivity from the hydrograph data. For the first procedure, termed K_e-*fitted*, K_e was adjusted until the runoff volume simulated by IRS matched the observed volume of the combined wet and very wet runs. The dry run was not used because of the difficulty of identifying parameters when the hydrograph is not at steady state. The combined wet and very wet runs were chosen because the combined volume minimizes measurement errors. For the second procedure, termed K_e-*solved*, K_e was estimated (Rawls et al., 1990) by solving equation 16 for K_e as:

$$K_e = \frac{i_{vw} - q_{vw}}{1 + \dfrac{(\eta_e - \theta_w)\,\psi}{F_{w+vw}}} \tag{29}$$

where

i_{vw} = rainfall rate at end of very wet run (L/T),
q_{vw} = discharge rate at the end of rainfall for the very wet run (L/T),
θ_w = volumetric water content at the beginning of the wet run (L/L), and
F_{w+vw} = cumulative infiltration depth for the combined wet and very wet run (L).

The parameter estimation procedure, termed IRS default, used the default parameter estimation of IRS. K_s was chosen from Table 1 based on the soil textural class of the plot. The K_e for site A1 was computed by equation 20. Simanton et al. (1991) reported that canopy cover had no statistical effect on infiltration for the grass dominated sites used in this analysis. Thus, the K_e for sites D1, D2, and H2 were computed using only the ground cover term in equation 20.

For the K_e-*fitted* and K_e-*solved* procedures, hydrographs for both the bare and natural treatments were simulated. Because the IRS default parameter estimation procedures do not have adjustments for the bare treatment, only the hydrographs for the natural treatment were simulated. A total of 24 hydrographs was simulated for each treatment (two plots per treatment, three runs per plot, four sites). The parameter values used in the simulation for the three procedures are listed in Tables 4 and 5.

RESULTS

The rainfall simulator experiment design is intended to produce steady state hydrographs. For the case of the bare treatment, steady state hydrographs were attained at all sites for the dry, wet, and very wet runs. However, for the natural treatment, steady state was rarely attained for the dry run and, for some sites, only attained during and after the high intensity application rate of the very wet run.

BARE TREATMENT

The purpose of using the K_e-*fitted* and K_e-*solved* procedures was to determine if the IRS model structure is compatible with the WEPP rainfall simulator experimental design. Application of the Green and Ampt equation in IRS

Table 4. Site average parameter values common to the three parameter selection procedures

Site	ψ mm	η_e mm / mm	θ_v mm / mm Dry	Wet	Chezy C $m^{0.5}/s$ b*	n†
A1	90	0.32	0.15	0.19	11.5	2.7
D1	110	0.46	0.27	0.33	8.1	1.6
D2	110	0.31	0.25	0.29	12.8	3.0
H2	310	0.51	0.21	0.25	10.1	2.3

* Bare treatment.
† Natural treatment.

Table 5. Effective saturated conductivity (mm/h) computed for the bare and natural plots

	Bare			Natural			
Site	Plot	K_e-*fitted*	K_e-*solved*	Plot	K_e-*fitted*	K_e-*solved*	IRS default
A1	32	2	1.2	31	35	33	32
	34	2	3.3	36	37	37	33
D1	72	2	1.2	71	8	5	14
	74	2	2.3	76	9	17	16
D2	78	5	1.2	77	20	14	15
	79	5	2.2	80	18	10	15
H2	120	1	0.8	119	5	5	0.84
	121	1	0.8	122	3	1	0.79

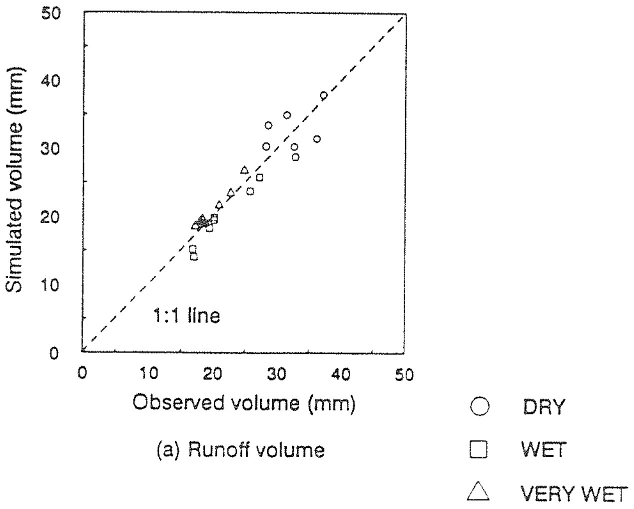
assumes uniform infiltration conditions on the entire plane while the kinematic wave model assumes broad sheet flow over the plane. Because the bare treatment results in a more uniform surface condition than exists with the natural treatment, the model should simulate the bare treatment hydrographs better than those of the natural treatment.

Parameter Identification. Both the K_e-*fitted* and K_e-*solved* procedures identified approximately the same K_e values for the bare treatment (Table 5). Figures 3a and 3b are scatter plots of observed versus simulated runoff volume and peak discharge, respectively, for the bare treatment simulations using the K_e-*fitted* procedure. The structure of the Green and Ampt and kinematic wave models appear to be applicable to the rainfall simulator bare treatment plots tested. The high r^2 for both the volume ($r^2 = 0.93$) and peak ($r^2 = 0.96$) for the combined dry, wet, and very wet simulations indicate that the model is capable of reproducing the observed runoff hydrograph over a range of soil moisture conditions for the bare treatment. The method of estimating K_e by matching the combined wet and very wet simulated volume with that of the observed gives consistent values of K_e for the dry run. Rawls et al. (1990) inferred crust formation from the difference between infiltration rates on screen covered and uncovered small plots adjacent to the bare plots for the sites used in this analysis. The fact that the same K_e value gives good results for the three runs indicates that, if crusting is a significant effect on infiltration on these plots, it occurs very early during the dry run. Note that the values for K_e for the bare treatment for all sites shows very little variation (Table 5). The small variation in K_e with soil texture suggests that the bare treatment effects which probably enhance crusting on the plot are more significant than any effects due to soil properties. It also suggests that trying to identify infiltration parameters and relating them to soil properties will be difficult if these rangeland bare plot data are used.

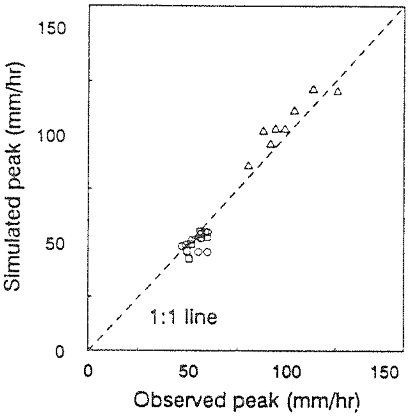
Figure 4 is a plot of the K_e-*fitted* and observed hydrographs for the dry, wet, and very wet runs for the bare treatment on plot 74, site DI. Inspection of figure 4 shows that both the simulated peak discharge and recession follows the observed very closely, but that the simulated runoff begins earlier. In general, IRS simulated the time of runoff start earlier than was recorded.

NATURAL TREATMENT

In contrast to the bare plots, the natural plots have a greater degree of surface cover variability which affects both the infiltration and overland flow response of the plot. Infiltration rates are generally higher on litter-covered surfaces and flow paths are more tortuous because of litter, rocks, and live vegetative matter on the soil surface. Thus, parameters identified for the natural treatment plots incorporate more averaging of surface characteristics than do the parameters identified for the bare treatment. The results from the natural treatment simulations reflect this averaging of the spatial variability on the natural plots.



(a) Runoff volume



(b) Peak discharge

Figure 3–Observed versus simulated (a) runoff volume (mm) and (b) peak discharge (mm/h) for the bare treatment using the K_e-*fitted* parameter selection procedure.

Parameter Identification. Figures 5a-5b and 6a-6b are scatter plots of observed versus simulated runoff volume and peak discharge, respectively, for the natural treatment plots for the K_e-*fitted* and K_e-*solved* parameter identification methods. The K_e-*fitted* procedure shows a better fit ($r^2 = 0.91$) than the K_e-*solved* procedure ($r^2 = 0.71$) for runoff volume (fig. 5a) over the range of initial soil moisture conditions. Although the number of plots is small, the K_e-*fitted* procedure identified a K_e value which gave relatively consistent results for a range of soil moisture conditions. As with the bare plot results, this suggests that, if crusting occurs, it occurs early during the dry run on most of these natural plots. The poorer results using the K_e-*solved* procedure for the natural treatment plots illustrate the weakness of requiring an estimate of the

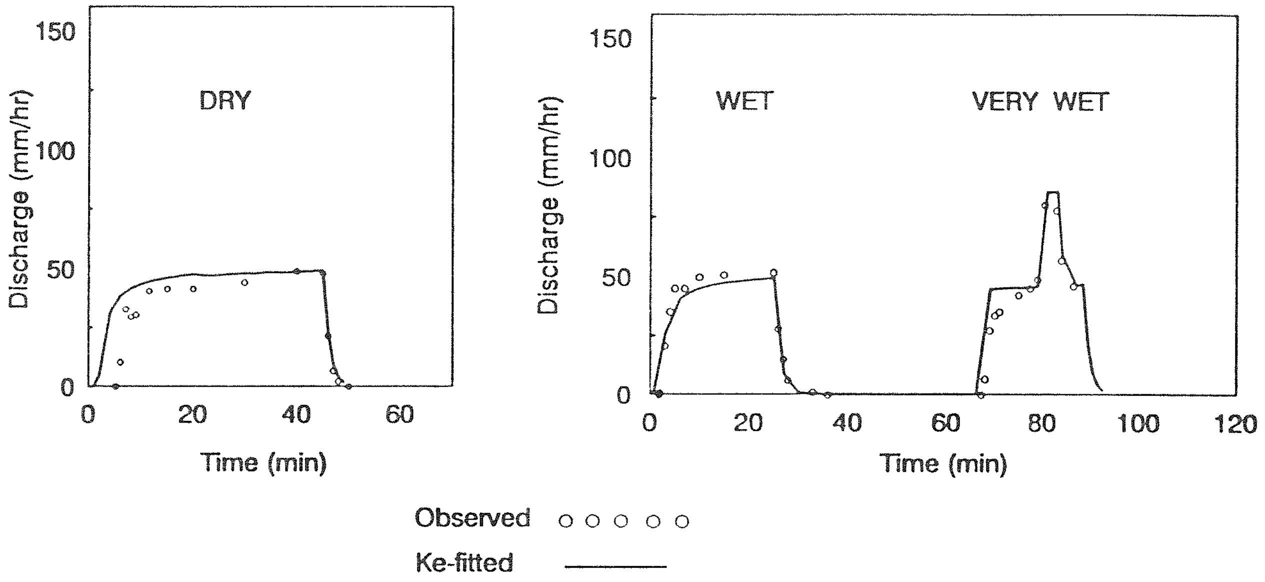


Figure 4–Runoff hydrograph for dry, wet, and very wet runs, Site D1, plot 74, bare treatment, using the K_e-*fitted* parameter selection procedure.

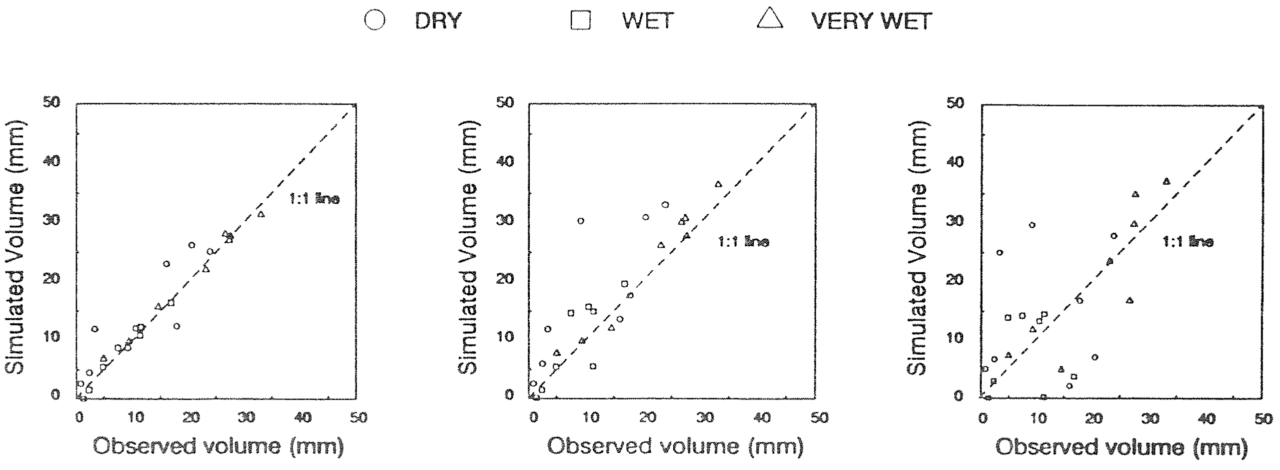
final infiltration rate in identifying K_e. For steady state hydrographs, as in the case of the bare plots, the assumption that $f_{vw} = i_{vw} - q_{vw}$ in equation 29 is valid. However, this assumption is not valid if the hydrograph is not at steady state as in the case for the natural treatment plots under low initial moisture conditions.

Parameter Estimation. Figures 5c and 6c are scatter plots of observed versus simulated runoff volume and peak discharge for the IRS default procedure. The default parameter estimation methods for K_e and ψ of IRS do a poor job overall in simulating runoff volume over the range of initial soil moisture conditions ($r^2 = 0.57$) but a good job for the very wet run ($r^2 = 0.86$). With the exception of site A1, the IRS default K_e was different than that identified by the K_e-*fitted* procedure. This is not surprising because equation 18 was developed using rainfall simulator data from plot similar in soil texture and vegetation to the natural plots of site A1. It is evident that a different relationship is needed to adjust K_s for cover and other factors such as macroporosity if IRS is to be applied to grass dominated sites. Therefore, default values of K_e in IRS should be used with caution.

Figure 7 is a plot of K_e-*fitted*, K_e-*solved*, and IRS default and observed hydrographs for the dry, wet, and very wet runs for the natural treatment, plot 122, site H2. As can be seen, both the K_e-*solved* and IRS default hydrographs match the very wet run well, but over predict the peak and volume for the dry and wet runs. The K_e-*fitted* hydrographs match all three runs much better.

SUMMARY

The program IRS was described and its application to parameter selection of rainfall simulator data was

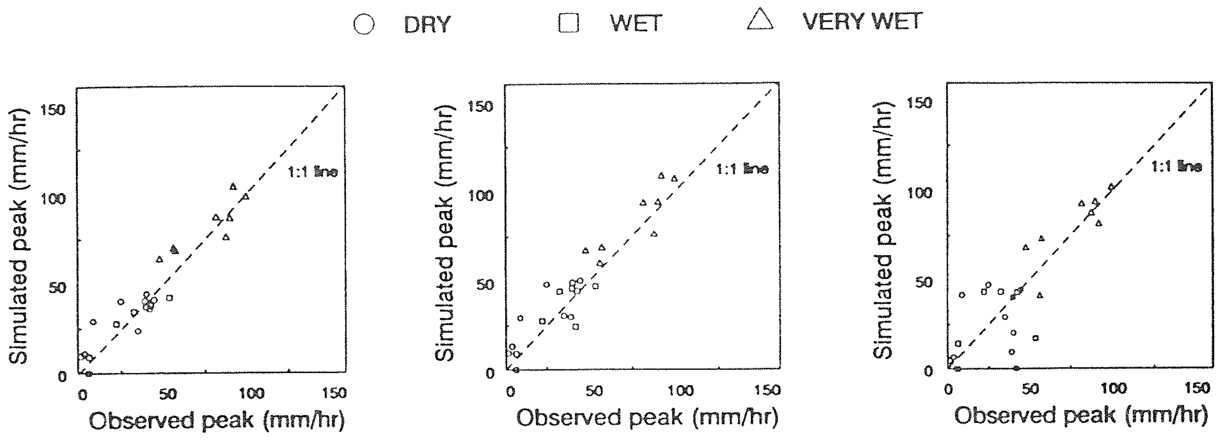


(a) Ke-fitted

(b) Ke-solved

(c) IRS default

Figure 5–Observed vs. simulated runoff volume (mm) for the natural treatment using the (a) K_e-*fitted*, (b) K_e-*solved*, and (c) IRS default parameter selection procedures.



(a) Ke-fitted (b) Ke-solved (c) IRS default

Figure 6–Observed vs. simulated peak discharge (mm/h) for the natural treatment using the (a) K_e-*fitted*, (b) K_e-*solved*, and (c) IRS default parameter selection procedures.

illustrated. The program computes infiltration using the Green and Ampt infiltration equation, rainfall excess as the difference between rainfall and infiltration independent of the routing equations, and the runoff hydrograph at the end of the plane using the kinematic wave model. A Newton Raphson iteration is used to solve the Green and Ampt equation and a semi-analytical method employing the method of characteristics is used to solve the kinematic wave model for overland flow on a single, homogeneous plane. Because the rainfall excess is computed independent of the hydrograph computations, partial equilibrium hydrographs and infinite duration of runoff occurs. These two physically unrealistic properties of the solution will not occur under normal applications of the model. The use of the model was illustrated using three parameter selection methods on data from rangeland rainfall simulator sites. It was shown that the structure of the model and the K_e-*fitted* procedure was successful at reproducing the runoff volume and peaks for both the bare and natural treatment rainfall simulator plots over a range of initial soil moisture conditions. The K_e-*solved* procedure which assumes that the final infiltration rate is equal to the rainfall rate minus the final discharge rate gave poorer results because the assumption that the hydrograph was at steady state was not always valid. The default parameter estimation methods imbedded in the IRS program was successful in simulating the hydrographs for the wet soil moisture condition but unsuccessful for the dry conditions. This was attributed to the adjustment of K_s to account for the effects of ground cover. The default parameter estimation methods imbedded in IRS need refinement in order to be applicable to grass covered surfaces.

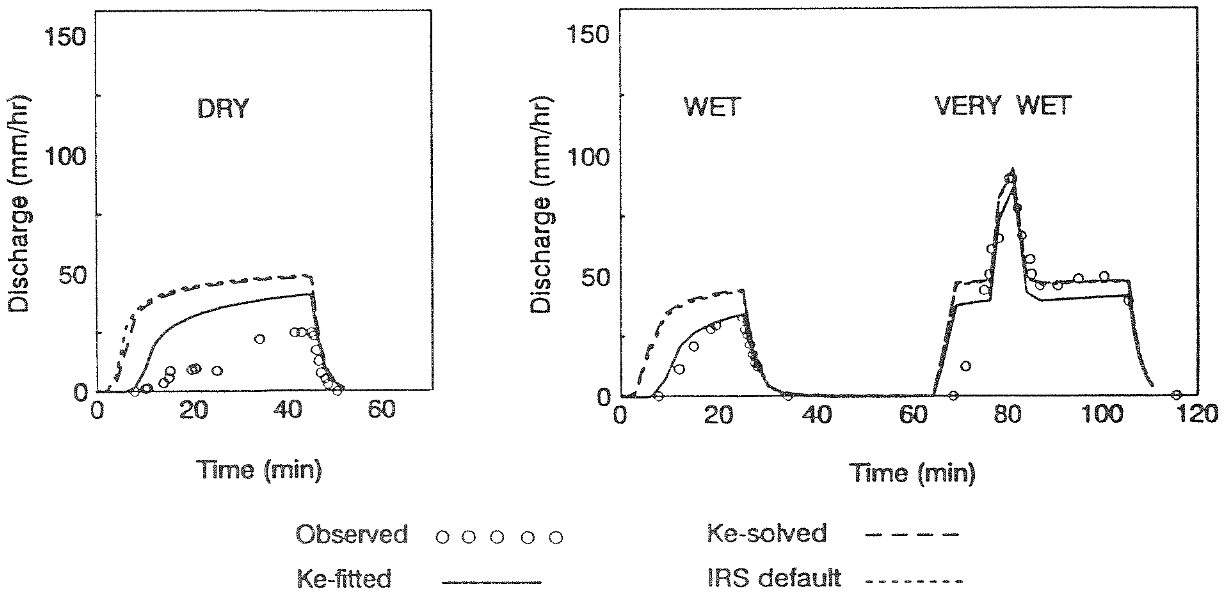


Figure 7–Comparison of runoff hydrographs for dry, wet, and very wet runs, Site H2, plot 122, natural treatment using the K_e-*fitted*, K_e-*solved*, and IRS default parameter selection procedures.

Although these results are based on only four sites, they show that the IRS model structure is robust on the sites tested over a range of initial soil moisture conditions and that consistent parameter values for the model can be identified. It should be emphasized that the K_e values identified for these plots are partly dependent on the value of ψ chosen from Table 1 and are specific to the Green and Ampt model. If different values of ψ are used, then different values of K_e will be identified.

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