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A STRIP MODEL APPROACH TO PARAMETERIZE A COUPLED GREEN-AMPT KINEMATIC WAVE MODEL[1]

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ABSTRACT: Infiltration processes at the plot scale are often described and modeled using a single effective hydraulic conductivity (K_e) value. This can lead to errors in runoff and erosion prediction. An integrated field measurement and modeling study was conducted to evaluate: (1) the relationship among rainfall intensity, spatially variable soil and vegetation characteristics, and infiltration processes; and (2) how this relationship could be modeled using Green and Ampt and a spatially distributed hydrologic model. Experiments were conducted using a newly developed variable intensity rainfall simulator on 2 m by 6 m plots in a rangeland watershed in southeastern Arizona. Rainfall application rates varied between 50 and 200 mm/hr. Results of the rainfall simulator experiments showed that the observed hydrologic response changed with changes in rainfall intensity and that the response varied with antecedent moisture condition. A distributed process based hydrologic simulation model was used to model the plots at different levels of hydrologic complexity. The measurement and simulation model results show that the rainfall runoff relationship cannot be accurately described or modeled using a single K_e value at the plot scale. Multi-plane model configurations with infiltration parameters based on soil and plot characteristics resulted in a significant improvement over single-plane configurations.
(KEY TERMS: infiltration; modeling; rainfall simulator; Green-Ampt model; Mein-Larson Equation.)

INTRODUCTION

Distributed hydrologic and erosion simulation models are increasingly adopting an infiltration based approach to compute runoff or rainfall excess. One of the most common infiltration models implemented is the Green-Ampt Mein-Larson (GAML) equation (Green and Ampt, 1911; Mein and Larson, 1973). GAML is used at the hillslope scale by the Water Erosion Prediction Project (WEPP) (Flanagan and Nearing, 1995) and CASC2D-SED (Johnson *et al.*, 2000) and at the watershed scale by HEC-1 (U.S. Army Corps of Engineers, 1998) and SWAT 2000 (King *et al.*, 1999). The GAML model offers the advantages of being physically based and sensitive to variations of intrastorm rainfall intensity, which can significantly affect the rates and amounts of runoff (see Skaggs and Khaleel, 1982, for a full description of the model). When coupled with physically based runoff and erosion models such as WEPP and CASC2D-SED, the resulting runoff rates can be used to compute flow shear and transport capacity necessary for calculating detachment and deposition rates of sediment.

There are two major considerations when using the GAML model to simulate infiltration and runoff: model parameterization and the scale at which the model needs to be applied to accurately model the processes. Parameter identification and estimation for the GAML model are not as widespread, compared to more established procedures such as the Curve Number (CN) method (SCS, 1972). The GAML infiltration parameter is an effective hydraulic conductivity (K_e) instead of a saturated hydraulic conductivity (K_s). The effective hydraulic conductivity term accounts for the fact that there is air entrapment in the soil and that the soil is not completely saturated during rainfall infiltration. The GAML infiltration parameters can be estimated based on soil texture using relationships developed by Rawls *et al.* (1982). This parameter estimation method is often used with distributed process based watershed models (e.g., WEPP, SWAT). However, as with the CN, a single infiltration parameter based on soil texture is often used to model infiltration over an entire hillslope or watershed (King *et al.*, 1999). Determination of the GAML effective

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hydraulic conductivity term for a specific area or watershed is not computed directly but computed as an inverse problem from observed rainfall and runoff rates (Stone *et al.*, 1992).

Data from instrumented watersheds have been used to parameterize coupled infiltration runoff models with varying degrees of success (Loague and Freeze, 1985; Goodrich, 1990; Loague and Kyriakidis, 1997). A cost effective method to determine infiltration parameters is to use some type of rainfall simulation experiment. Rainfall simulator experiments have the advantages of obtaining large amounts of data quickly and being able to control initial conditions and inputs to the system (Lusby and Lichty; 1983, Simanton *et al.*, 1991; Alberts *et al.*, 1995). The most extensive database of rainfall simulator data used to parameterize the GAML model is from the Water Erosion Prediction Project (WEPP) and Interagency Rangeland Water Erosion Team (IRWET) (Franks *et al.*, 1998) experiments. The WEPP and IRWET rangeland experimental designs consisted of three rainfall simulator runs: a dry run under initial moisture conditions, a wet run 24 hours later, and a very wet run 30 minutes after the end of the wet run (see Simanton *et al.*, 1991, for more detail). The simulator experiments were conducted on a range of soil and vegetation complexes on rangelands across the west. Lusby and Lichty (1983) also conducted rainfall simulator experiments to develop best fit parameters for the GAML model on four soil vegetation complexes in Colorado.

The Lusby and Lichty (1983) and the WEPP-IRWET experiments used multiple application rates during a simulation run, and both data sets show similar results – an increase in steady state infiltration rate with increasing rainfall application rate. This relationship is shown in Figures 1a and 1b where the apparent final infiltration rate is plotted versus the application rate for Plots 1 and 2 from Lusby and Lichty (1983) and selected sites of the WEPP experiment. The locations as well as the soil and vegetation characteristics for the sites in Figures 1a and 1b are listed in Table 1. The WEPP data are the average of two plots from the very wet run with two rainfall application rates, 50 to 60 and 90 to 120 mm/hr. For sites dominated by brush (Figure 1a) and by grass (Figure 1b), most of the final infiltration rates increase with the higher application rates.

An increased steady state infiltration rate with increasing rainfall application rate is often called partial area contribution or response. Hawkins (1982) and Morin and Kosovsky (1995) also have shown this type of response. Hawkins (1982), using rainfall simulator plot data from Utah, showed that the apparent infiltration rate changes with rainfall intensity. The reason put forth was that there is a distribution of infiltration capacities for a given area, as a function of the area's variability of soils and vegetation. As the application rate is increased, more of the plot area will begin to contribute. However, these newly contributing areas have higher infiltration capacities, and thus the apparent plot infiltration rate increases. For example, infiltration studies on sagebrush sites have shown significant differences between infiltration rates under and outside the canopy areas (Blackburn *et al.*, 1975; Johnson and Gordon, 1988; Balliette *et al.*, 1986). Therefore, at a single application rate, only those areas of the plot that have an infiltration

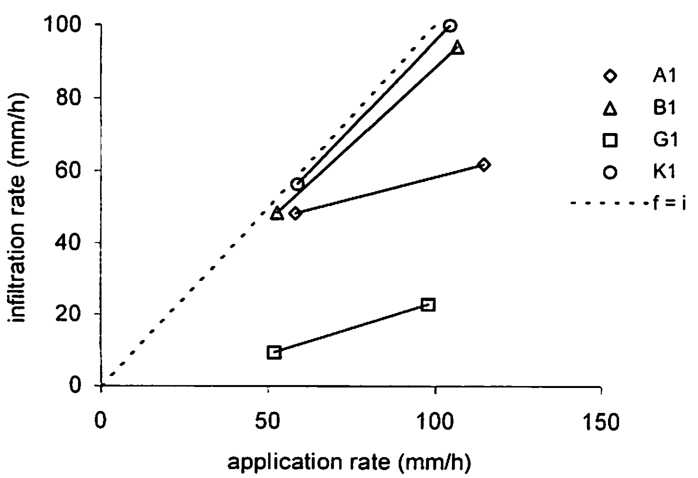

Figure 1a. Application Rate Versus Final Infiltration Rate for Selected Brush Dominated Rangeland Sites From the WEPP Experiments.

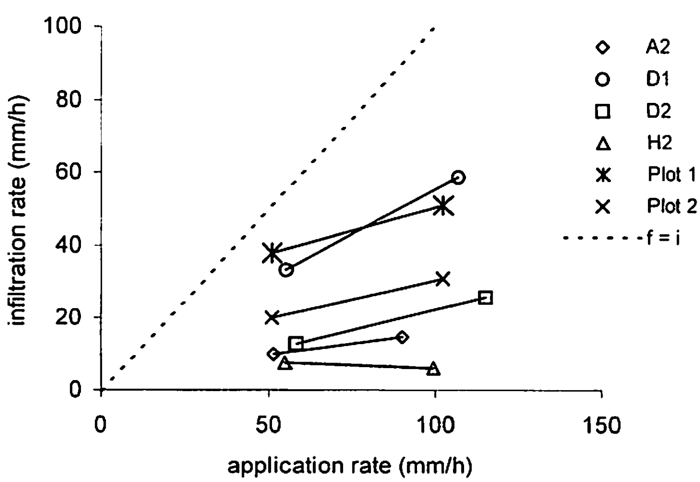

Figure 1b. Application Rate Versus Final Infiltration Rate for Selected Grass Dominated Rangeland Sites From the Lusby and Lichty (1983) and WEPP Experiments.

TABLE 1. Cover and Soil Characteristics for Selected Rangeland Sites of the Lusby and Lichty (1983) and WEPP Experiments.

Site	State	Community	Ground Cover (percent)	Canopy Cover (percent)	Soil Texture
Plot 1[a]	Colorado	Short grass prairie	nr[b]	nr	Clay loam
Plot 2	Colorado	Short grass prairie	nr	nr	Clay loam
A1	Arizona	Chihuahuan desert shrub	40	18	Gravelly Sandy loam
A2	Arizona	Chihuahuan desert grass	40	18	Sandy clay Loam
B1	Nevada	Great Basin shrub	67	17	Gravelly fine Sandy loam
D1	Oklahoma	Tallgrass prairie[c]	90	64	Loam
D2	Oklahoma	Tallgrass prairie[c]	90	53	Very fine Sandy loam
G1	Colorado	Salt desert shrub steppe	42	11	Silty clay
H2	South Dakota	Mixed grass prairie	80	20	Clay
K1	California	Sagebrush	82	20	Gravelly Sandy loam

[a]Plots 1 and 2 are from the Lusby and Lichty (1983) experiment and the remainder of the sites are from the WEPP experiment.
[b]Not reported (see *Methods and Materials* for a description of canopy and ground cover).
[c]Former cropland reverted to rangeland.

capacity less than the application rate will contribute to runoff. Rainfall simulator studies that use only one application rate will identify infiltration rates or parameters that may be intensity specific (Hawkins, 1982).

The parameter identification methods for the GAML model from multiple intensity rainfall simulator experiments have varied. Rainfall simulator plots are often evaluated and modeled as a single overland plane. Lusby and Lichty (1983) used trial and error to fit the GAML parameters and the kinematic wave model Manning's n for the rainfall simulator runs on natural plots in Colorado. Although they obtained good fits to the observed hydrographs, the value of the GAML matric potential term was on the order of 2 to 8 mm, considerably lower than values reported by Rawls *et al.* (1982) and the conductivity term was not consistent among runs on the same plot. For WEPP, Alberts *et al.* (1995) only used the wet run data of the natural treatment plots to develop optimized GAML hydraulic conductivity terms. They used the WEPP model to estimate the matric term, adjusting that term with the site soil porosity and initial soil water conditions, and then adjusted the hydraulic conductivity term until the simulated runoff volume matched the observed volume.

In hydrologic models, the GAML hydraulic conductivity term is assumed to be constant during a single rainfall runoff event; however, using a single value of the conductivity term cannot reproduce the observed increase in infiltration rate with increased application rate. To account for the variability of infiltration capacity within an area, Woolhiser and Goodrich (1988) and Goodrich (1990) divided overland flow elements into a series of strips perpendicular to the contour lines, herein after referred to as the strip model approach. They assumed a lognormal distribution of the hydraulic conductivity term of the Smith-Parlange infiltration equation in the KINEROS model, and hydraulic conductivity values were assigned to each strip using an optimized coefficient of variation and a lognormal distribution. This approach approximated the theoretical variability of infiltration across the plot but did not address the relationship between the optimized coefficient of variation and soil and cover characteristics. We hypothesized that determining the relationship between the spatial variability of infiltration and the soil and cover characteristics would improve our ability to model hydrologic and erosion processes.

This paper describes a method to parameterize the GAML infiltration model using a variation of the strip model approach of Woolhiser and Goodrich (1988) to address observed increases in steady-state infiltration rate with increasing rainfall application rate. A rainfall simulator experiment was conducted on five 2 m by 6 m field plots on a rangeland watershed in southeastern Arizona. The GAML effective hydraulic conductivity term for a modified version of KINEROS was obtained for two types of plot configuration: the first assumed that the entire plot was contributing to runoff, and the second assumed that the contributing area changed with rainfall intensity and was a function of the percentages of bare soil and litter, surface cover and grass canopy, and shrub canopy. The objectives of the study were to: (1) evaluate the relationship between rainfall intensity and runoff, (2) integrate measurement and modeling techniques to identify GAML parameters over a range of rainfall intensities, and (3) evaluate the effectiveness of using a strip-model approach to represent the variability of infiltration on natural plots.

METHODS AND MATERIALS

The field research for this study was conducted on the Kendall subwatershed 112 (Figure 2) on the Walnut Gulch Experimental Watershed (WGEW) located within the San Pedro River Valley in southeastern Arizona. The 152-km^2 WGEW is a semi-arid brush and grassland complex in the transition zone between the Sonoran and Chihuahuan deserts (Renard *et al.*, 1993). Rainfall is distributed as thunderstorms of short duration, limited areal extent, and high intensity causing most of the annual runoff in the summer months, and long duration and low intensity frontal air mass rainfall over large areas producing little runoff during the winter months. Kendall 112 is a zero order grassland watershed of 1.91 hectares with an average slope of 9.4 percent. The Natural Resources Conservation Service (NRCS) classifies the majority of WGEW as within Major Land Resource Area 41-3 and the Kendall watershed as being in ecological site Loamy Uplands with Limey Slopes inclusions (Arizona Field Office Technical Guide, http://www.az.nrcs.usda.gov/fotg/home.htm). The soils on Kendall 112 are mapped as an Elgin-Stronghold complex and are gravelly fine sandy loams with an average bulk density of 1.40 g/cm^3. Vegetation consists of warm season midgrasses including black gramma (*Bouteloua eriopoda*), blue gramma (*Bouteloua gracilis*), and curly mesquite (*Hilaria belangeri*), with brush species such as burroweed (*Happlopappus tenuisectus*), whitethorn (*Accacia constricta*), Yucca (*Yucca spp.*), and ocotillo (*Fouqueria slendens*). Lane *et al.* (1995) delineated three overland flow paths, each of which originates at the upper boundary of the hillslope and terminates at the outlet of the watershed. Five rainfall simulator plots measuring 2 m by 6 m were installed along two of these overland flow paths within the subwatershed.

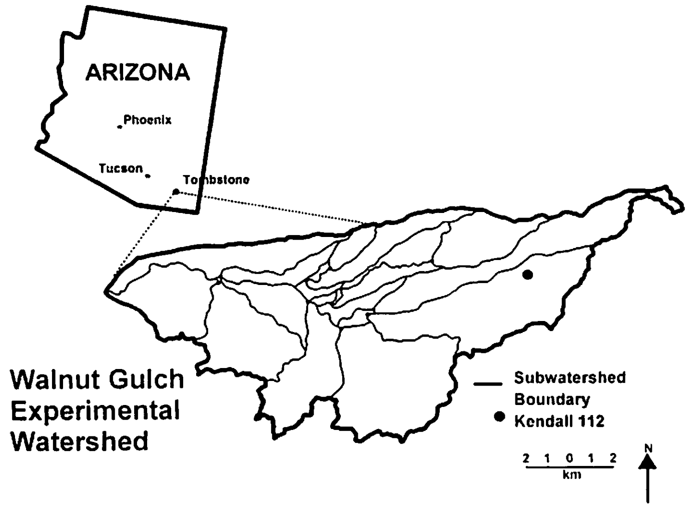

Figure 2. Map Showing Location of Walnut Gulch Experimental Watershed and Kendall 112 Subwatershed.

Rainfall Simulator Experiments

A computer controlled, variable intensity rainfall simulator similar to the Purdue simulator (Neibling *et al.*, 1981) was used in the study. The simulator has a central oscillating boom six meters long with four Veejet 80100 nozzles attached at 1.52 m intervals and can apply intensities between 50 and 200 mm/h over a 2 m by 6.1 m plot. A computer is used to control a stepper motor, which in turn controls both the rate that the sprinkler nozzles move across the plot and the duration that they spray on and off the plot. The rate that the nozzles move across the plot is variable such that the rate is faster across the center of the plot and slower toward the sides to ensure uniform coverage over a 2 m width. The distribution of the applied rainfall across a 2 m by 6 m area has a measured coefficient of variability (CV) of less than 10 percent. The duration that the nozzles spray off the plot determines the application rate or intensity with longer durations corresponding to low intensities and short durations to higher intensities. The entire simulator is covered with windbreaks to minimize the effects of spray drift, and four total depth rain gauges are installed on the plot to check the application depth. For all the runs reported in this study, the difference between the gages and computed depths was less than 5 percent. The computer control allows the user to change the applied intensity without stopping the simulator.

Two rainfall simulator runs – a dry run under natural initial conditions and, one hour later, a wet run – were conducted on each plot. For each simulator run, the rainfall application was continuous and started with the higher intensities and decreased incrementally to 50.8 mm/h (2 in/h). The intensities and the order of application for each simulator run conducted on the plots are presented in Table 2. Most runs concluded with a high intensity so we could observe the recession limb of the hydrograph and calculate the surface storage on the plot. Variations in the rainfall intensities applied for the different plots were due to water supply limitations and difficulties encountered with some of the equipment during the simulator runs. Each intensity was applied until steady state runoff was maintained for a minimum of five minutes.

TABLE 2. Rainfall Simulator Runs Conducted on the Field Plots in Kendall 112. The intensities are presented in the order in which they were applied.

		Applied Rainfall Intensities (mm/h)*					
Plot 1	Dry	177.8	127.0	76.2	76.2	50.8	
	Wet	177.8	127.0	76.2	50.8	177.8	
Plot 2	Dry	177.8	127.0	76.2	50.8	127.0	
	Wet	177.8	127.0	76.2	50.8	127.0	
Plot 3	Dry	127.0	76.2	50.8	177.8		
	Wet	177.8	127.0	76.2	50.8	177.8	
Plot 4	Dry	177.8	127.0	76.2	50.8	177.8	
	Wet	177.8	152.4	127	76.2	50.8	177.8
Plot 5	Dry	177.8	127.0	76.2	50.8	177.8	
	Wet	177.8	152.4	127.0	76.2	50.8	177.8

*Duration of any specific intensity was variable. Each intensity was maintained until steady state runoff was observed for at least five minutes.

Runoff depths were measured at the end of the plot using a precalibrated flume attached to an ISCO 4200 Flow depth gauge. The runoff depths were converted to discharge rates using the flume rating curve and the entire plot area (Simanton *et al.*, 1991). Soil moisture was measured before and during the simulator runs at eight locations within each plot using CS615 Water Content Reflectometer probes (Campbell Scientific, Inc.). The probes measure the volumetric moisture content of porous media using time domain measurement methods. The measured dialectic conductivity of the porous media was converted to volumetric moisture content using individual calibration curves developed for each plot. (The USDA neither guarantees nor warrants the standard of products mentioned, and the use of the name by the USDA implies no approval of the product to the exclusion of others that may also be suitable.)

Plot Characteristics

Detailed measurements of the microtopography and surface and vegetative cover were made on each plot. The surface and vegetative cover characteristics were measured at 480 points on a 10 cm by 25 cm grid on each plot using the point line method (Bonham, 1989). At each measurement location, a pointer was dropped straight down and the canopy cover and surface cover were identified. The vegetative canopy cover was classified as shrub, forb, grass, cactus, or none. The surface cover characteristics were classified as soil (no surface cover), litter, basal, rock (more than 20 mm), or gravel (5 to 20 mm). The microtopography was measured at the same 480 points using a total station.

Hydrologic Simulation Model

The KINEMAT model (Woolhiser *et al.*, 1990), a research version of KINEROS2 (Smith *et al.*, 1995), was used to analyze the results of the rainfall simulator experiment. KINEMAT computes infiltration and runoff on a single overland flow plane or a cascade of overland flow and channel elements. Infiltration is computed interactively with rainfall excess being routed using a numerical solution of the kinematic wave equation. For this study, the Smith-Parlange infiltration component was replaced with the GAML equation. The form of the GAML equation used to determine the cumulative infiltration depth is

$$K_e t = F(t,x) - (1-\theta_i) n_e \Psi \ln\left(1 + \frac{F(t,x)}{(1-\theta_i) n_e \Psi}\right) \qquad (1)$$

where K_e = effective hydraulic conductivity (L/T), t = time (T), x = distance (L), F = cumulative infiltration (L), θ_i = initial soil moisture (L/L), n_e = effective porosity (L/L), and Ψ = average matric potential across the wetting front (L). Infiltration is computed under two distinct conditions, before and after surface ponding has occurred. Before ponding, the infiltration rate is equal to the rainfall rate and the cumulative infiltration depth is equal to the cumulative rainfall. After time to ponding, a Newton-Raphson iterative solution is used to solve Equation (1) for cumulative infiltration. The average infiltration rate (f) for a time interval is determined using

$$f_{i-1}(t,x) = \frac{F_i(t,x) - F_{i-1}(t,x)}{t_i - t_{i-1}} \quad (2)$$

where i is the current time.

The rainfall in excess of the infiltration rate is routed using the kinematic wave equations for flow on a plane. The kinematic wave equations are the continuity equation

$$\frac{\partial h}{\partial t} + \frac{\partial q}{\partial x} = r_c(t,x) \quad (3)$$

and the depth-discharge relationship

$$q(t,x) = \alpha h(t,x)^m \quad (4)$$

where h = depth of flow (L), t = time (T), q = discharge per unit width (L^2/T), r_e = rainfall excess rate (L/T), α = depth discharge coefficient, and m = depth discharge exponent. For this study, the Chezy depth discharge relationship was used so that m = 1.5 and α = C $S^{0.5}$ where C is the Chezy coefficient ($L^{0.5}$/T) and S is the slope of the plane (L/L).

Model Parameterization and Configuration

The GAML infiltration model requires soil moisture, porosity, matric potential, and effective hydraulic conductivity, K_e, as parameters. Soil moisture and porosity were computed from the soil moisture probes and bulk density measurements, respectively. The matric potential term was estimated from the soil texture of the plots using relationships derived by Rawls *et al.* (1982). As the soils on all five plots are gravelly fine sandy loams, a matric potential of 90 mm was used for all plots. Parameterization of K_e is discussed below. The Chezy coefficient for the kinematic wave model was computed from the hydrograph recession as described by Woolhiser (1975).

Two methods were used to determine the effective hydraulic conductivity parameter – an optimization method and a computational method. For both methods, the dry run was used to obtain the parameters, and the wet run was used as validation. For the optimization method, the conductivity term K_e-opt was adjusted until the computed runoff volume equaled the observed runoff volume (Stone *et al.*, 1992). The effective hydraulic conductivity for the single plane plot configuration was parameterized using Ke-opt.

The strip model configurations used both the optimization and a computed method to determine the effective hydraulic conductivity terms. Two configurations, a two plane and a three plane, were parameterized. The planes were configured with the flow length parallel to the direction of overland flow. It was assumed that only the areas of bare soil and litter were contributing to the start of runoff. It has been demonstrated numerous times in the literature that bare soil areas have a lower hydraulic conductivity and infiltration capacity than vegetated areas (Simanton *et al.*, 1991; Dunne *et al.*, 1991; Morin and Kosovsky, 1995). Under this assumption, an effective hydraulic conductivity of bare areas, $K_e$tp, can be computed from the GAML time to ponding equation as

$$K_e tp = \left(\frac{i^2 t_p}{(1-\theta_i) n_e \Psi + i t_p} \right) \quad (5)$$

where t_p = time to ponding (T) and i is the initial rainfall intensity (L/T). For the two plane configuration, the first plane, with an area equivalent to the area of bare soil and litter, was parameterized using $K_e$tp. For the second plane, a second effective conductivity representing the remaining "covered" area, K_{ec}, was obtained by adjusting its value until the total simulated runoff volume from the two planes matched the observed runoff volume. From field observations during the simulation run, it appeared that very little runoff originated under the shrub canopy. Therefore, for the three plane configuration, it was assumed that the shrub areas did not contribute to runoff and that the total contributing area equaled the bare soil areas outside the shrub canopy and the grass canopy areas. The effective hydraulic conductivity for the plane representing the grass canopy area was optimized using the same method described above. A schematic of the three plot configurations and their respective hydraulic conductivity parameters is presented in Figure 3.

The conductivity terms obtained from the dry run were validated using the data from the wet run. Both the results for the two methods of obtaining the conductivity terms from the dry and wet runs were evaluated using the root mean square error, RMSE. The statistic uses the sum of the squares of the differences between the measured and the predicted values as

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(X_i - Y_i)^2} \quad (6)$$

where Y is the measured runoff rate, X is the predicted runoff rate, and the index i represents the different application rates. The test statistic was calculated for both the dry and wet rainfall simulator runs using the steady state runoff rate for each applied rainfall intensity during a run. A small root mean of the square of the differences between measured and predicted steady state runoff rates indicates that the model configuration is able to simulate the observed runoff rates and their changes with applied intensities.

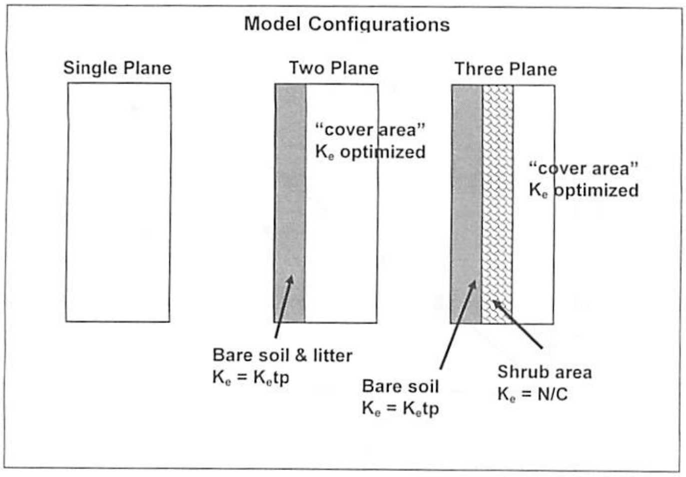

Figure 3. Schematic Showing the Three Configurations Used to Model the Observed Infiltration and Runoff Processes on the Five Plots.

RAINFALL SIMULATION RESULTS

The relationship between the calculated steady-state infiltration rates for the applied rainfall intensities for the dry and wet runs are shown in Figure 4. In all cases, there is an increase in steady-state infiltration with rainfall intensity. It is not clear that the maximum infiltration rate, the point at which the entire plot is contributing to the observed runoff, has been reached. For that to be evident, there would be no change in infiltration rate with change in rainfall intensity. In all cases, the calculated infiltration rate for an applied intensity is higher for the dry run than the wet. This result was expected due to the changes in initial soil moisture within the plots between runs.

The observed changes in infiltration rate with intensity are not as great for the wet runs as for the dry runs. Differences between the plots can be seen in the range of infiltration rates and their variability among the plots. For the dry runs, four of the plots, Plots 2 through 5, the calculated infiltration rate was equal to the applied rainfall intensity for the lowest intensity indicating that the lowest infiltration rate on the plot is greater than 50.8 mm/h for that antecedent moisture condition. For Plots 1, 3, and 5, the infiltration rate for the lowest intensity decreased on the wet run. However, the calculated infiltration rates at the highest applied intensity (177.8 mm/h) varied among all the plots and ranged from 80.58 mm/h on Plot 3 to 121.73 on Plot 2. Plot 2 consistently had the highest infiltration rates from both the dry and wet rainfall simulator runs. Plot 3 had the lowest infiltration rates for the wet run, while Plot 1 had the lowest rates for the wet run. The calculated infiltration rates for Plots 4 and 5 are almost identical for the wet runs, with the only difference observed for the 76.2 mm/h intensity.

Plot Characteristics

The summary cover characteristics (Table 3) indicate differences among the five plots. The variability among the plots is lowest for percent litter and soil. It is relatively high (79 percent) for percent shrub, but when evaluating total canopy cover, the CV is 31 percent. Plot 3 has the lowest percent of canopy cover and no shrubs and the highest percent of bare soil. Plot 5, on the other hand, has the highest percentage of canopy cover (72 percent), primarily grass, while Plot 4 has the highest percentage of shrubs (16 percent) and the lowest percentage of grass cover. All of the plots had a large percentage of surface litter (37 to 52 percent). This means that for the two plane configurations, the area of plane 1, parameterized using K_etp, was at least 50 percent of the plot.

There were discernible differences among the plots; however, it is not clear what effect the plot characteristics had on the observed hydrologic response. A simple correlation analysis was conducted for observed infiltration rates, lowest and highest rates for the dry and wet runs, and measured plot characteristics (percent soil, litter, shrub, canopy cover). Significant positive correlations ($\alpha = 0.10$) were found between percent soil and the lowest infiltration rate ($r = 0.660$) and percent shrub and the high infiltration rate ($r = 0.509$) for the dry runs. There were no significant relationships between the plot characteristics and the observed infiltration rates for the wet runs.

The measurement results from the rainfall simulator experiments illustrate the varying relationships among rainfall intensity, infiltration capacity, and antecedent moisture conditions on rangeland plots. The measured infiltration rates from the five rainfall simulator plots within a zero order watershed ranged from 39 mm/h to 114 mm/h for the dry run and 51

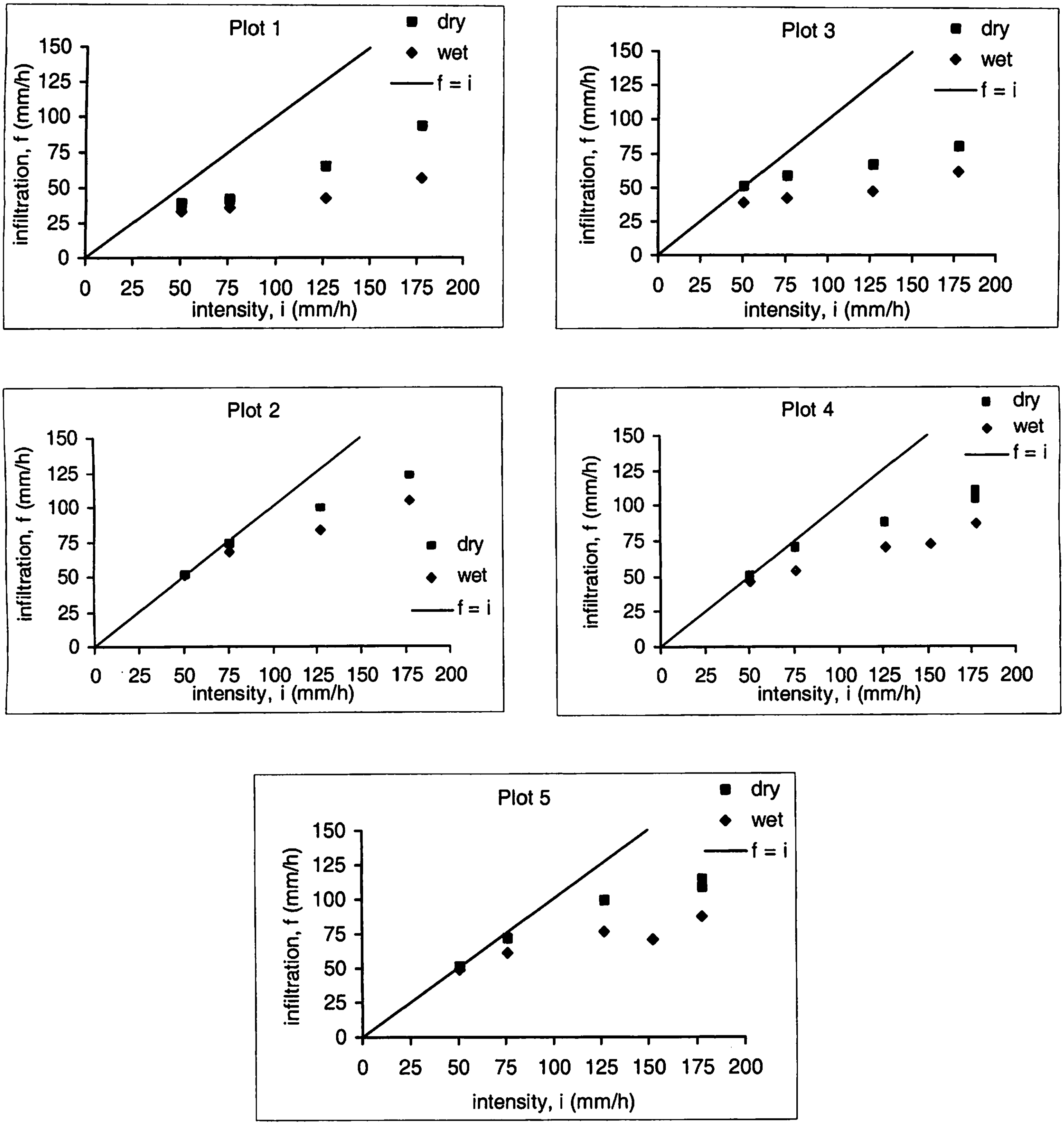

Figure 4. Relationship Between Steady State Infiltration Rate and Rainfall Intensity for the Dry and Wet Rainfall Simulator Runs on the Five Plots.

mm/h to 101mm/h for the wet run (Figure 4). These results indicate that using a single infiltration parameter to define a site with moderate to significant variability of soil and or cover characteristics may result in infiltration rates and derived infiltration parameters with significant error over the range of rainfall intensities expected to cause runoff.

MODEL RESULTS

The optimized K_e values are presented in Table 4 along with the measured and predicted peak runoff rates from the dry and wet rainfall simulator runs. The optimized K_e values for the single plane configurations ranged from 27 mm/h (Plot 1) to 52 mm/hr

TABLE 3. Summary of Surface and Vegetative Canopy Cover Characteristics From the Point Measurements Made on the Field Plots.

	Plot 1	Plot 2	Plot 3	Plot 4	Plot 5	CV (percent)
Surface						
Soil (percent)	9	13	16	15	10	24
Litter (percent)	45	52	42	37	51	14
Basal (percent)	8	9	14	16	20	37
Rock (percent)	14	10	9	19	12	31
Gravel (percent)	23	16	19	13	7	39
Slope (percent)	9	14	12	11	12	16
Canopy						
Shrub (percent)	9	9	0	16	4	79
Forb (percent)	1	1	0	0	0	137
Grass (percent)	40	45	34	21	68	42
Cactus (percent)	0	2	0	0	0	224
Total Canopy (percent)	50	57	34	37	72	31

TABLE 4. Single K_e Values Determined for each of the Field Plots for the Dry Simulator Runs and the Observed and Predicted Peak Runoff Rates for the Dry and Wet Runs Using the Single Plane Configuration.

	K_e-Opt (mm/h)	Chezy C ($m^{0.5}/s$)	Dry Run Peak Runoff (mm/h)		Wet Run Peak Runoff (mm/h)		Percent Difference	
			Measured	Predicted	Measured	Predicted	Dry	Wet
Plot 1	26.7	8.39	84.02	111.02	120.75	138.57	32	15
Plot 2	52.0	4.96	56.07	70.85	73.56	104.80	26	39
Plot 3	28.0	2.40	97.22	130.71	115.90	143.78	34	24
Plot 4	39.7	4.33	73.56	112.40	90.53	128.75	66	42
Plot 5	49.6	4.17	69.53	102.55	90.53	113.58	47	25

(Plot 2). They represent an average of the observed variability of the infiltration capacities for the soil moisture conditions within each plot for the dry runs. The model results from the dry runs for the single plane configurations did not match the rise or peak of observed hydrograph very well. In general, the simulated hydrographs overestimated the time to ponding and the peak runoff rate and slightly underestimated the hydrographs for the smaller rainfall intensities. As can be seen in the results in Table 4, in general the simulated hydrographs for the wet runs using the single optimized K_e value from the dry run did much better at matching the observed maximum peak runoff rate, except for Plot 2. Though the maximum peak runoff rate was still overestimated in all cases as is the runoff volume, the results from the wet run are much better at matching the time to ponding and rising limb of the observed hydrographs. These results were expected because of the observed changes in steady state infiltration rate with changes in the applied intensity as well as the differences between the dry and wet simulator runs presented in Figure 4. There was less change in infiltration rate with intensity on the wet runs (less variability) than on the dry runs. However, it was evident for both the dry and the wet runs, that the observed hydrograph cannot be simulated using a single hydraulic conductivity parameter and that there are differences between the runoff response for the dry and wet simulator runs.

The resulting effective hydraulic conductivity terms that were used to parameterize the two plane and three plane strip model configurations are presented in Table 5 along with the representative area of each plane. As with the single plane K_e values presented in Table 4, there are differences among the plots for the optimized K_e values as well as the time to ponding $K_e$tp values. It is important to note that for the two plane configuration, the optimized K_e for Plane 2 is 178 mm/h or greater for Plots 2, 4, and 5. This means that Plane 2 is not contributing to the

TABLE 5. Effective Hydraulic Conductivity Values for the Two Plane and Three Plane Configurations. The representative area of each plane is presented (in parentheses) below each K_e value.

	Two Plane		Three Plane		
	Bare Soil and Litter $K_e$tp (mm/h)	Cover Area K_e Optimized (mm/h)	Bare Soil $K_e$tp (mm/h)	Cover Area K_e Optimized (mm/h)	Shrub Area* (mm/h)
Plot 1	26.69 (54.0%)	26.60 (46.0%)	26.69 (9.0%)	20.70 (82.25%)	NC (8.75%)
Plot 2	33.16 (65.0%)	178.00* (35.0%)	33.16 (13.3%)	58.75 (77.3%)	NC (9.4%)
Plot 3	12.04 (58.3%)	102.0 (41.7%)	N/A	N/A	N/A
Plot 4	14.60 (51.9%)	178.00* (48.1%)	14.60 (15.0%)	54.82 (69.2%)	NC (15.8%)
Plot 5	14.01 (61.2%)	178.00* (38.8%)	14.01 (10.4%)	52.90 (85.6%)	NC (4.0%)

*NC indicates that the plane is not contributing to the runoff.

simulated runoff because its optimized K_e value is higher than the highest applied rainfall intensity. For the three plane configurations, it is assumed that Plane 3 (representative of the area of shrubs) does not contribute to the simulated runoff.

In general, the multiple plane strip model approach improved the ability to simulate the observed peak runoff rate for both the dry and wet rainfall simulator runs. Comparisons of the measured and predicted peak runoff rates for the multiple plane configurations are presented in Table 6 along with the results from the single plane configurations. The percent difference between measured and predicted rates decreased in all cases, except Plot 1. There was little

TABLE 6. Comparison of Observed and Predicted Peak Runoff Rates for the Dry and Wet Runs for All Three Plot Configurations.

		Dry Run Peak Runoff (mm/h)		Wet Run Peak Runoff (mm/h)		Percent Difference	
		Measured	Predicted	Measured	Predicted	Dry	Wet
Plot 1	One-Plane	84.02	111.02	120.75	138.57	32	15
	Two-Plane	84.02	112.20	120.75	138.97	34	15
	Three-Plane	84.02	106.59	120.75	130.54	27	8
Plot 2	One-Plane	56.07	70.85	73.56	104.80	26	39
	Two-Plane	56.07	66.15	73.56	82.88	15	13
	Three-Plane	56.07	69.05	73.56	97.66	23	32
Plot 3	One-Plane	97.22	130.71	115.90	143.78	34	24
	Two-Plane	97.22	100.21	115.90	121.49	3	5
Plot 4	One-Plane	73.56	112.40	90.53	128.75	66	42
	Two-Plane	73.56	100.54	90.53	91.04	37	0.1
	Three-Plane	73.56	85.44	90.53	113.12	16	25
Plot 5	One-Plane	69.53	102.55	90.53	113.58	47	25
	Two-Plane	69.53	91.05	90.53	94.56	31	4
	Three-Plane	69.53	100.06	90.53	110.34	44	22

difference between the results for the single plane and two plane configurations for Plot 1; the $K_e$tp value (Table 5) was very close to the average K_e optimized on runoff volume (Table 4). This meant that there was relatively no difference in the K_e values used to parameterize the two plane configuration. The addition of the third plane (decreasing the area contributing to the runoff) resulted in a lower optimized K_e value for Plane 2 and a better fit of the observed peak runoff. However, for the other plots there is a marked improvement in the ability to match the observed peak runoff using a multiple plane configuration. For the dry runs, the percent differences range from 3 percent (Plot 2, two plane) to 44 percent (Plot 5, three plane). The differences for the wet runs range from 0.1 percent (Plot 4, two plane) to 32 percent (Plot 2, three plane). The measured and predicted comparisons in Table 6 are only evaluating the ability of the model configurations to match the observed peak runoff and not the ability to simulate the observed hydrographs.

Comparison of Hydrographs

The measured and simulated hydrographs for the single plane and multiple plane configurations from Plots 3 and 5 are presented in Figure 5. These plots show the best (Plot 3) and worst (Plot 5) results from the simulation model. Because there are no shrubs on Plot 3, only the single plane and two plane configurations were simulated. No single multi-plane configuration was consistently better for all the runs. The one plane and three plane configurations for the dry run on Plot 5 both underestimated the rise of the hydrograph and overestimated the peak runoff. The two plane configuration, on the other hand, matched the rise well but overestimated the runoff rate at all of the intensities. For the wet run, the two plane configuration matched the rise and the peak runoff well but overestimated the runoff at the lower intensities. The three plane configuration matched the observed runoff at the lower intensities. For Plot 3, the two plane configuration did significantly better at matching the observed hydrographs than the one-plane configuration on both runs. It matched the observed peak runoff rate and did better at simulating the rise of the hydrograph.

Results from the three model configurations were compared and evaluated to determine the optimum configuration to accurately model the observed runoff. The resulting RMSE statistics for the dry run are presented in Table 7. The minimum RMSE for each plot is highlighted in bold indicating the model configuration that was "best" at simulating the runoff rates for each of the simulator runs. The results show that not a single model configuration consistently outperformed the others. However, it is important to note that using a two plane or three plane configuration resulted in lower RMSE values than the single plane configuration on all of the plots. The lowest calculated RMSE was for Plot 3, which had an error value of 9.48 mm for the two plane configuration. Because there are no shrubs on Plot 3, the two plane and three plane configurations are the same. For Plot 2, there was no improvement in model results using the two plane configuration instead of the single plane. This is most likely attributable to the high $K_e$tp, 33.16 mm/hr and the fact that the second plane does not contribute in this case. The plot with the highest minimum RMSE was Plot 5. This reflects the difficulty in modeling the observed hydrograph presented in Figure 4. It is important to note that for Plot 4, the plot with the largest percent of shrub, the two plane configuration does best at simulating the observed hydrograph.

There was an improvement in the ability to simulate the observed hydrographs on the dry runs using the three plane configuration, especially on Plots 1, 2, and 5. However, when strictly evaluating the ability of the model to match the maximum peak runoff rate, the two plane configuration did a better job on the dry runs. This is illustrated in Table 6, which compares the measured and observed maximum peak runoff rates from the dry runs.

The root mean square errors (RMSE) for the wet runs are presented in Table 8. In general, the test statistics are lower for the wet runs than the dry runs, indicating a better ability to simulate the observed hydrograph. Plot 1 had the lowest RMSE for all of the wet runs using the dry run parameters with an error value of 6.78 mm for the three plane configuration. Plots 2 and 5, the plots with the most complexity, had the worst model efficiency statistics. The inconsistency in the results among plots when comparing the different model configurations indicates that the characteristics of the plots and their hydraulic properties have a significant bearing on the "optimum" configuration to be used in order to model the hydrologic response. Though the models were not optimized on runoff volume for the wet runs, the resulting values are very close to the observed (Figure 6). All three model configurations overpredicted the runoff volume for Plot 2. However, both the two plane and three plane configurations are an improvement over the single plane.

The difficulty in modeling the observed hydrographs from a single simulator run with variable rainfall intensity applications was evident in all the plots. A single plane configuration with a K_e value optimized on runoff volume is a lumped average of the

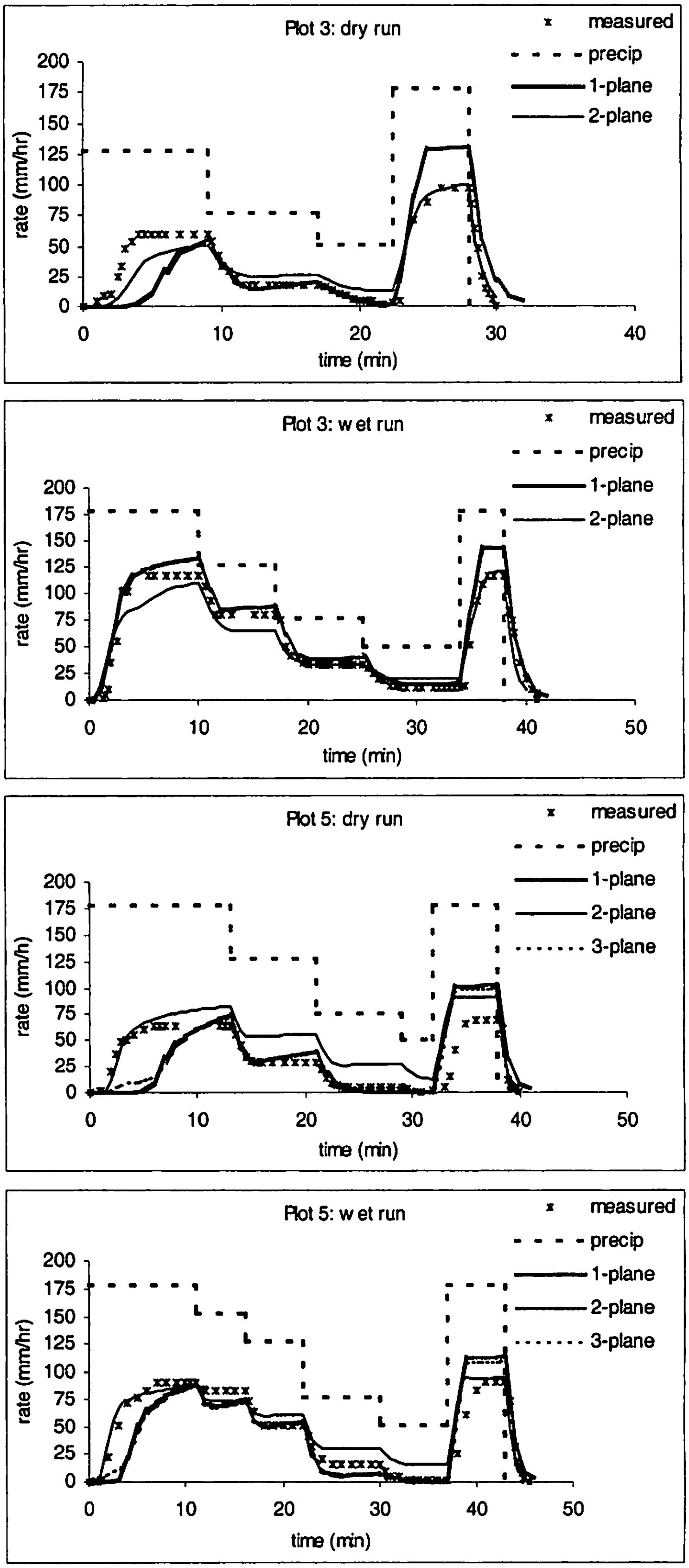

Figure 5. Comparison of Measured and Predicted Runoff Hydrographs for the Dry and Wet Runs From Plots 3 and 5.

TABLE 7. Root Mean Square Error Statistics (mm) of Observed Versus Predicted Steady State Runoff Rates for the Dry Runs Calculated Using Equation (6).

	One Plane	Two Plane	Three Plane
Plot 1	15.86	15.49	**12.23**
Plot 2	12.37	12.38	**11.51**
Plot 3	17.01	**9.48**	9.48*
Plot 4	20.33	**13.72**	15.32
Plot 5	16.26	21.32	**15.15**
Average	16.37	14.48	**12.74**

*Two plane and three plane configurations are the same for Plot 3.

TABLE 8. Root Mean Square Error Statistics (mm) of Observed Versus Predicted Steady State Runoff Rates for the Wet Runs Calculated Using Equation (6).

	One Plane	Two Plane	Three Plane
Plot 1	9.35	9.32	**6.78**
Plot 2	19.62	**11.13**	15.91
Plot 3	15.39	**8.07**	8.07*
Plot 4	19.49	**7.21**	10.79
Plot 5	10.75	10.31	**9.71**
Average	14.92	**9.21**	10.25

*Two plane and three plane configurations are the same for Plot 3.

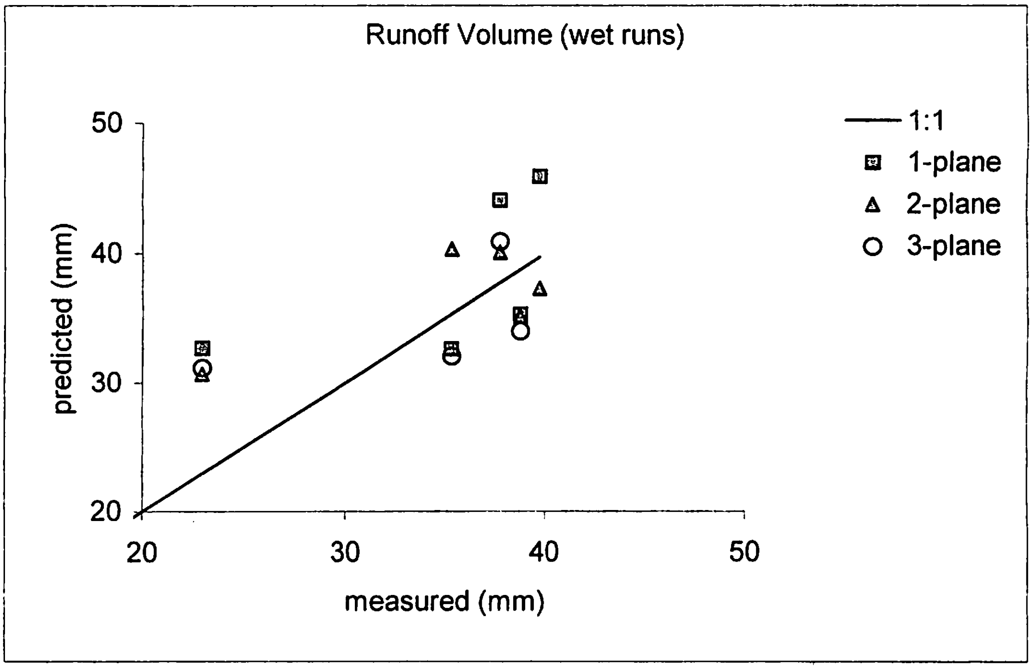

Figure 6. Comparison of Measured and Predicted Runoff Volume for the Wet Runs From All Five Plots.

response and usually overestimates the time to ponding and the peak runoff rate. In general, the results were better for the wet runs than for the dry runs. In all cases, a multi-plane configuration was an improvement over the single plane configuration. No single multi-plane configuration was consistently better for all of the runs. Overall, the three plane configuration was better for the dry run and the two plane configuration was better for the wet runs.

DISCUSSION AND CONCLUSION

The rainfall simulator experiments showed the changes in infiltration rate that occur at the plot scale in response to changes in rainfall intensity and initial soil moisture conditions. Using a single fitted K_e value, it was difficult to match the observed peak runoff rates from the rainfall simulator runs on all five field plots. In most cases, the single plane configuration was able to match the lower intensity runoff well but overestimated the runoff from the higher intensities. In general, the simulated hydrographs from a single K_e were a much better fit on the wet runs than the dry runs, both in matching the time to ponding and the rise in the hydrograph.

Using a multi-plane strip model configuration, either a two plane or three plane strip approach, resulted in an improvement over the single plane configuration. In some cases, because of the large percentage of litter on the plots, simply reducing the time to ponding hydrograph using the area of soil and litter also resulted in an overestimation of runoff volume and peak runoff rate. The configurations that performed best were the configurations that had large differences in the K_e values for the separate planes, again indicating the spatial variability of the infiltration capacity within each of the plots and the importance of accounting for that variability in simulation models when it exists.

The fact that significant statistical relationships between steady state infiltration rates and canopy cover were not found is contrary to results from other plot studies that have found statistical correlations between cover characteristics and measured infiltration rates (Simanton *et al.,* 1991; Tromble *et al.,* 1974). This result is attributable to three factors. First, the results from the previous studies compared results from distinctly different watersheds (grassland and brush) with different soils. In this study, all the plots are within the same 1.9 ha area watershed, and we are only comparing five plots. Also, most of the other studies used only a single rainfall intensity making the differences between plots more distinct. The third factor that became evident during the course of this study is the limitations of the plot characterization method that was used. The point line method provides the percentages of each of the cover attributes that are identified. This produces plot average values that are easy to compare among distinct land types. When plots within the same watershed are compared, the plot average cover characteristics may not be as distinct, even though the hydrologic responses may be different.

The strip model approach in this study used the plot characteristics to determine the infiltration parameters within each plot. However, the strip model approach does not account for the interaction of these areas with different infiltration capacities within the plot. The current method of characterizing plots is not adequate for parameterizing distributed hydrologic models to simulate the run on and runoff processes that occur down the length of the plot. We theorize that a measurement method that maps the interspace and covered areas, their relative locations, and connectivity would improve our ability to parameterize distributed models.

The most significant results presented in this study are: (1) that steady state infiltration rate does vary with rainfall intensity and the amount of variability changes with initial soil moisture; (2) a single hydraulic conductivity term should not be used to describe the infiltration processes at the plot scale; (3) there were significant differences in K_e values when comparing among plots within the same subwatershed; and (4) measured plot characteristics could be used to improve model parameterization and configuration. Though still a simplification of the complex processes of run on and runoff that occur on flow planes during rainfall events, discretizing and parameterizing the plots into two or three planes based on plot characteristics significantly improved the ability to model the observed hydrographs from the rainfall simulator experiments. Accurate estimations of peak runoff rates on rangelands at plot and/or watershed scales are important for evaluating land management practices and making land use decisions. The strip model configurations parameterized using K_e values attributable to the plot characteristics significantly improved the ability to simulate the observed hydrograph and the peak runoff rate. This was achieved using the GAML infiltration model and applied over a large range of rainfall intensities and different initial soil moisture conditions.

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