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Infiltration and Runoff Response from a Complex Soil Plot

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Abstract

An integrated measurement and modeling study was conducted to evaluate the effects of plot complexity and differences in soil hydrologic response on measuring and modeling infiltration and runoff processes. Experiments using a variable intensity rainfall simulator were conducted on a 2 m by 6 m soil box lysimeter packed with two soils with different infiltration capacities with two different plot configurations. Rainfall application rates varied between 50 and 200 mm/hr. Results of the rainfall simulator experiments found differences between the hydrologic responses of the two soils to changes in applied rainfall intensity. The study also showed that the location of the two soils relative to each other in the soil box did have an important effect on runoff response and that the response changed with changes in rainfall intensity. A distributed, process based hydrologic simulation model was used to model the complexity of the plots. The results of the simulation model showed the difficulty in accurately modeling the hydrologic response from heterogeneous soil plots.

Introduction

Hydrologic processes on hillslopes are highly variable in space and time due to the nature of the climatic input, topography, soils, vegetation and land use. The hydrologic response of an area is influenced substantially by the soil's infiltration capacity, which is significantly affected by both the temporal variability of precipitation and the spatial variability of soil and vegetation properties. Infiltration, due to its inherent spatial variability, has a significant effect on runoff processes and is one of the most important processes in hydrologic and erosion modeling.

Process based, distributed hydrologic simulation models often use lumped average infiltration parameters to simulate distributed processes across a hillslope. A single infiltration rate or a lumped average is often used to define the infiltration capacity of an area without considering the location of areas of high and low infiltration capacity (Woolhiser and Goodrich, 1988). Lumping of distributed parameters can lead to distortions in the results of distributed, process based models (Lane et al., 1995). A primary concern is not the determination of the lumped average, but quantification and distribution of the variability of infiltration rates over a given area. Measurement of the variability of vegetation and soil properties is relatively easy; however, quantifying the effects of that variability on the infiltration process is much more difficult. This is due in part to difficulties in quantifying the spatial distribution of infiltration on a hillslope.

Rainfall application rate is an important factor to consider when using rainfall simulators to determine the spatial variability of infiltration at both the point and plot scales (Hawkins, 1982). The use of the point measurements to describe the infiltration processes at the plot scale has been shown to improve at higher rainfall intensities. Dunne et al. (1991) found that infiltration rate varied with flow depth, and that rainfall intensity had a strong effect on the apparent infiltration rate on short hillslopes. Rainfall intensity influenced flow depth along the slope and therefore had a secondary effect on the spatial pattern of infiltration.

In this study, a rainfall simulator experiment was conducted to evaluate the relationship between rainfall intensity and hydrologic response on soil plots with two different soil configurations. The objectives of the study were to 1) determine the importance of relative locations of higher and lower infiltration capacity on runoff response and 2) determine how, and if, the relationships among soil hydraulic response, soil location on the flow plane and rainfall intensity change with changes in rainfall intensity.

Methods

Rainfall simulator experiments were conducted using a newly developed variable intensity rainfall simulator on a 2 m by 6 m soil box lysimeter. The soil box was built into the ground and has a depth of 0.6-m and a slope of 7%. The soil box was divided lengthwise down the middle to form two plots. Each plot was packed with two soils, a Bernardino fine sandy loam and a mixture of Bernardino (50%) with a sand (50%) (referred to as the Mixed soil in this paper), using the configuration shown in Figure 1. Note that the left plot has the Bernardino upslope and the Mixed soil down slope while the right has the reverse configuration. The saturated hydraulic conductivity (Ksat) of the Bernardino soil, measured in the laboratory with a constant head permeameter, was 66 mm/hr while the Ksat of the Mixed soil was 250 mm/hr. The bulk densities of the Bernardino and Mixed soils were 1.51 g/cm^3 and 1.59 g/cm^3, respectively. It was assumed that if the Ksat values of the two soils were significantly different that the hydrologic response of the two soils also would be significantly different. The soil box was instrumented with 16 calibrated soil moisture probes (Fig. 1) to measure the changes in soil moisture content in the top 7 cm of the soil during the simulations. Runoff flow depths were measured at the down slope end of each plot using a pre-calibrated flume connected to an ISCO 4200 flow depth gauge (Simanton et al., 1991)[1].

The rainfall simulation events were conducted using a computer controlled variable intensity rainfall simulator developed at the USDA-ARS Southwest Watershed Research Center and is based on previous simulators developed by Meyer and McCune (1958) and the USDA-ARS Soil Erosion Laboratory (Norton, L.D., 1995, personal communication). The simulator has a central oscillating boom six meters long with four V-Jet 80-100 nozzles and can apply rainfall intensities between 50 and 200 mm/hr on a 2 m by 6 m plot. The computer control allows the user to change the intensity without stopping the simulator. The distribution of the applied rainfall across a 2 m by 6 m area has a measured coefficient of variability (CV) less than 10% for all intensities used in the experiment. The experimental procedure consisted of applying a series of rainfall intensities from 50.8 mm/hr to 177.8 mm/hr

[1] The USDA neither guarantees nor warrants the standard of the product, 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.

on both plots simultaneously. The intensity was increased using 25.4 mm/hr increments. The rainfall applied to the two plots was measured using non-recording rain gauges. A given intensity was applied until the runoff discharge rate was at steady state for a minimum of 5 minutes on both plots. The steady state infiltration rate was computed as the difference between the applied rainfall intensity and steady state runoff rate.

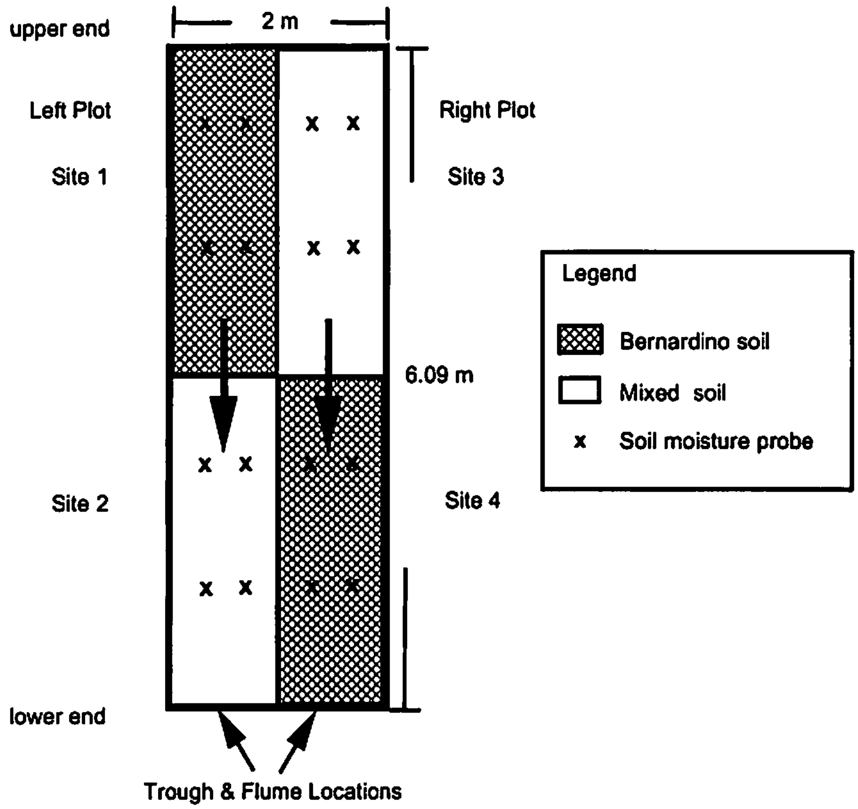


Fig. 1. Soil box configuration showing position of soils and measurement locations.

A total of eight rainfall simulation runs were conducted on the soil box. Three runs termed "continuous" were conducted such that the application rate was varied after both plots had reached steady state runoff. Five runs termed "discrete" were conducted such that the application rate was changed after runoff had ceased on both plots. Two continuous runs and one discrete run were conducted on the entire two plot system to evaluate the differences between the two plots and how the relative location of the soils within each plot influenced changes in hydrologic response with changing rainfall intensity. One continuous run and four discrete runs were conducted on the lower sites (Site 2 and Site 4, Figure 1) to determine the hydrologic response of the two individual soils. Both the results from the simulator runs on the lower two sites and the results from the entire two-plot system were evaluated using a distributed, process based hydrologic simulation model.

Results

Individual soils

In evaluating the results of the five simulator runs conducted on the lower two sites, it was determined that the soils did have different hydrologic responses. Both runoff volumes and steady state discharge rates for the two soils were statistically significantly different from each other for each of the simulator runs (0.04>P>0.00).

The relationship between steady state infiltration rate and rainfall intensity was significantly different between the two soils. As shown in Figure 2, the steady state infiltration rate of the Bernardino soil was relatively constant with increasing rainfall intensity. The effect of the rainfall intensity on the resulting calculated infiltration rate was tested for the Bernardino soil using linear regression analysis. The slope of the regression line was not significantly different from zero indicating that there was no change in the apparent infiltration rate with change in applied rainfall intensity and that there was no change in the contributing area to runoff. It is possible that the hydrologic response of the Bernardino soil was in part due to sealing of the soil surface.

In contrast to the Bernardino soil, the calculated infiltration rate for the Mixed soil increased with increasing rainfall intensity (Fig. 2). This relationship was seen in all five of the rainfall simulator runs and is an indication of partial area response. This means that there is spatial variability of the infiltration capacity within the plot and not all areas of the plot are contributing equally to the measured runoff at steady state (Hawkins, 1982). This is most likely caused by a non-uniform distribution of the sand across the plot and the interaction of the sand and the Bernardino soil decreasing the ability of the fine particles in the Bernardino soil to seal the surface. It is not clear from Figure 2 that the final infiltration rate for this soil had been reached because the steady state infiltration rate appears to be still increasing. To insure that the final rate had been reached, higher rainfall intensities would have to be applied until the change in the infiltration rate equals the change in applied intensity. It is important to note that these results show that, even on a bare soil of relatively homogeneous surface characteristics, the apparent infiltration rate can be significantly influenced by variations in rainfall intensity.

Entire soil box

Differences in runoff volume and peak discharge between the two plots were found in all three of the simulator runs. A direct comparison of the measured runoff volumes and peak runoff rates for the individually applied intensities from the discrete run found a significant difference (P = 0.00) between the left and right plots.

The relationship between measured infiltration rate at steady state and applied intensity for a continuous run is shown in Figure 3. In this case, a continuous simulator run was conducted first with an increase in rainfall intensity (50.8 mm/hr to 177.8 mm/hr in 25.4 mm/hr increments). After runoff ceased on the plot, the same intensities were applied in a continuous run in decreasing order. The results presented in Figure 3 are the average of the steady state infiltration values at each of the applied intensities.

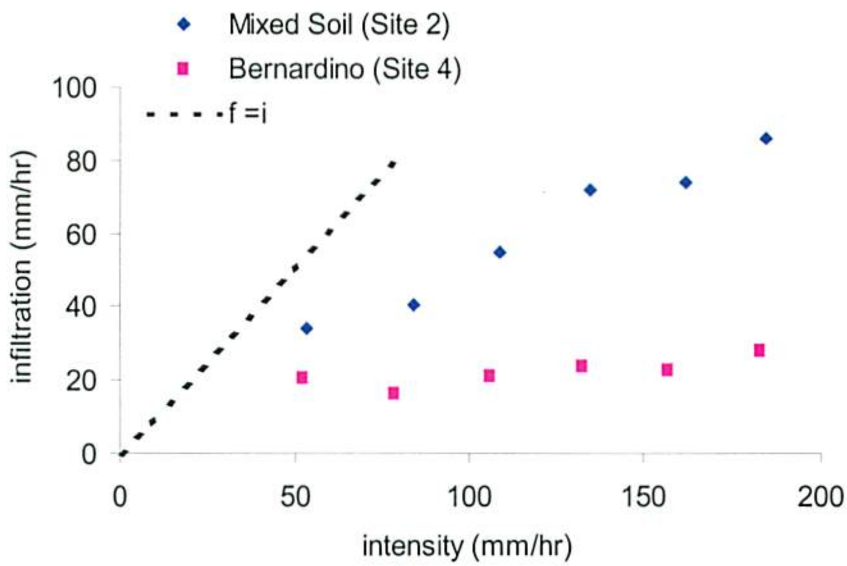


Fig. 2. Comparison of the average steady state infiltration rate as a function of applied rainfall intensity from the lower two sites.

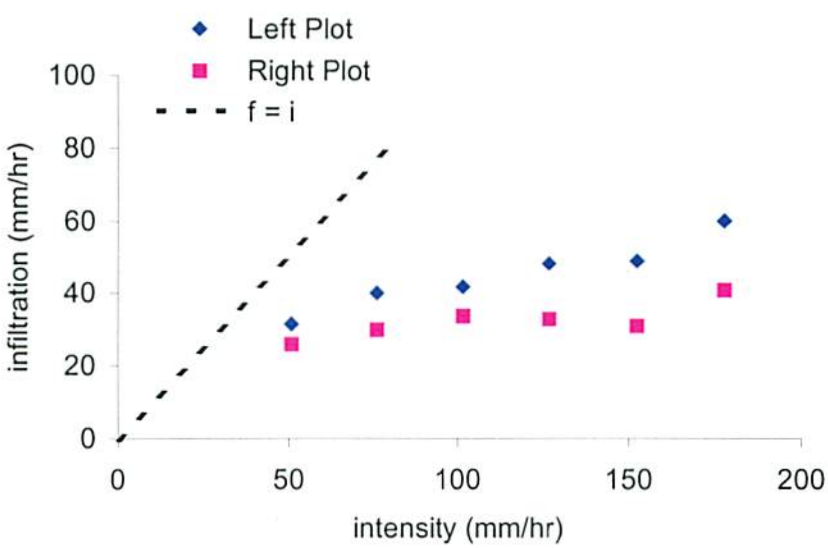


Fig. 3. Comparison of the average steady state infiltration rate as a function of applied rainfall intensity from the left and right plots.

The addition of a second soil above the lower two soils (Sites 2 and 4, Figure 1) changed the relationship between intensity and plot response. The difference in the steady state infiltration rate between the left and the right plots has decreased (Fig.3). The addition of the Bernardino soil above the Mixed soil appears to have damped the effects of the partial area response on the left plot. The infiltration rate vs. intensity curve for the left plot (Fig. 3) is much flatter than the infiltration rate vs. intensity curve for the Mixed soil alone (Fig. 2). The addition of the Mixed soil plane above the Bernardino soil on the right plot, resulted in an increase in the infiltration rate with increased intensity. However, because the Bernardino soil is located at the lower end of the plot, the change of infiltration rate with intensity is not as great on the right plot. The higher infiltration rates on the left plot are probably due to runoff from the Bernardino soil infiltrating into the Mixed soil on the lower site. It is not evident from Figure 3 that the final infiltration rate had been attained for either plot. As with the individual mixed soil, higher rainfall intensities would have to be applied sequentially in order to determine the true final infiltration rate for each plot.

Modeling

A distributed, process based simulation model was used to evaluate the effects of the two-soil plot configuration on our ability to model infiltration and runoff processes on a complex plot. The runoff model that was used is a modification of KINEROS (Smith et al., 1995) which computes infiltration using the Green-Ampt Mein-Larson (GAML) (Mein and Larson, 1973) equation and the runoff hydrograph using the kinematic cascade model. The GAML model requires soil moisture, porosity, matric potential, and effective saturated hydraulic conductivity, K_e, as parameters. Soil moisture and porosity were computed from the soil moisture probes within each site and bulk density samples, respectively. The matric potential term was computed from soil texture using relationships derived by Rawls et al. (1982). The K_e term was fit by adjusting its value until the computed runoff matched the observed runoff. The kinematic wave model requires two parameters, the coefficient and exponent of the depth-discharge relationship. The Chezy relationship was used for this study, so the exponent was 1.5 and the Chezy roughness coefficient was computed from the hydrograph recession as described by Woolhiser (1975).

Two different fitting procedures were used, lumped and discrete. For the lumped procedure, one K_e value was computed for each of the plots and KINEROS was run using a single plane configuration. For the discrete procedure, each plot was modeled as a two plane configuration corresponding to the two soil sites within each plot. For this configuration, K_e values had to be determined for both soils and involved two steps.

First, the K_e was determined for the two lower soil sites by adjusting K_e for each soil until the runoff volume from the model matched the measured values from the individual soil runs. However, because infiltration increased with rainfall intensity on the Mixed soil shown in Figure 2, there was a large difference in K_e values. The optimized K_e values for the Mixed soil (Site 2) from the discrete simulator runs ranged from 2.5 mm/hr to 59 m/hr, with an average K_e of 18.9 mm/hr and a standard deviation of 12.7 mm/hr. For the Bernardino soil (Site 4), the optimized K_e values from the discrete simulator runs ranged from 1.1 mm/hr to 7.4 mm/hr with an average K_e of 3.52 mm/hr and standard deviation of 2.14 mm/hr.

The measured and predicted runoff hydrographs for the Mixed and Bernardino soils for a continuous run are presented in Figure 4. For the Mixed soil, using a single optimized value of K_e (21.6 mm/hr) in the model resulted in an under-estimation of runoff at the lower intensities and an over-estimation at the higher intensities, which is consistent with the results shown in Figure 2. In comparison, the computed hydrograph for the Bernardino soil using the optimized K_e (5.15 mm/hr) matches well with the observed hydrograph, indicating that a single value of K_e is sufficient and also consistent with Figure 2. For the second step it was decided to use the average optimized K_e value from the Bernardino soil (Site 4) to parameterize the Sites with Bernardino soil in each of the plots (Sites 1 and 4) to model the 2-plane configuration. In this case, the average K_e value of 3.52 mm/hr was used to parameterize Sites 1 and 4. The same optimization procedure was then used to determine the K_e values for the Mixed soil planes (Sites 2 and 3.) The K_e values were adjusted until the simulated runoff volume matched the observed. The resulting optimized K_e values were 58 mm/hr for Site 2 and 46 mm/hr for Site 3.

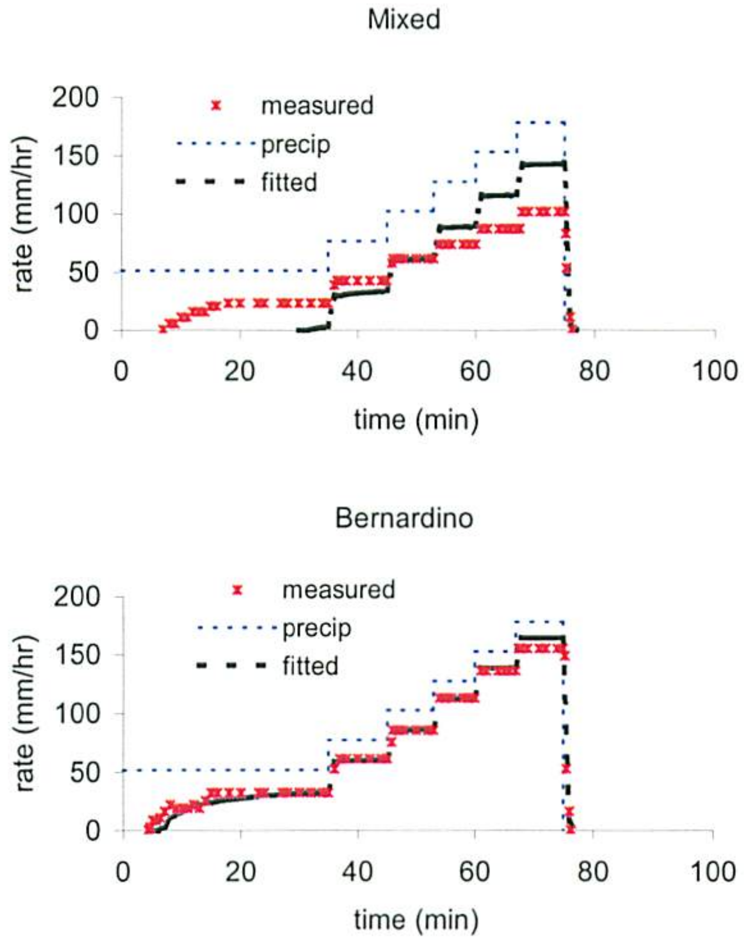
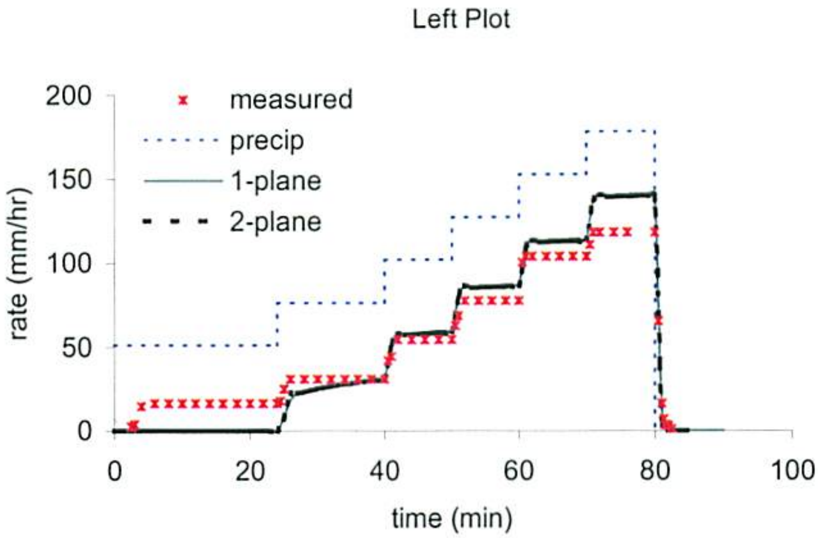


Fig. 4. Comparisons of measured and predicted hydrographs for the individual soils from a continuous simulator run.

The hydrographs for the two plots for a continuous simulator run are presented in Figure 5. Each graph shows the hydrograph computed using a single lumped value of K_e to define each plot and the hydrograph computed using two values of K_e (two-planes) to define each plot. For both the left and right plots, using a single K_e underestimated the runoff at the lower intensities and overestimated the runoff at the high intensities.



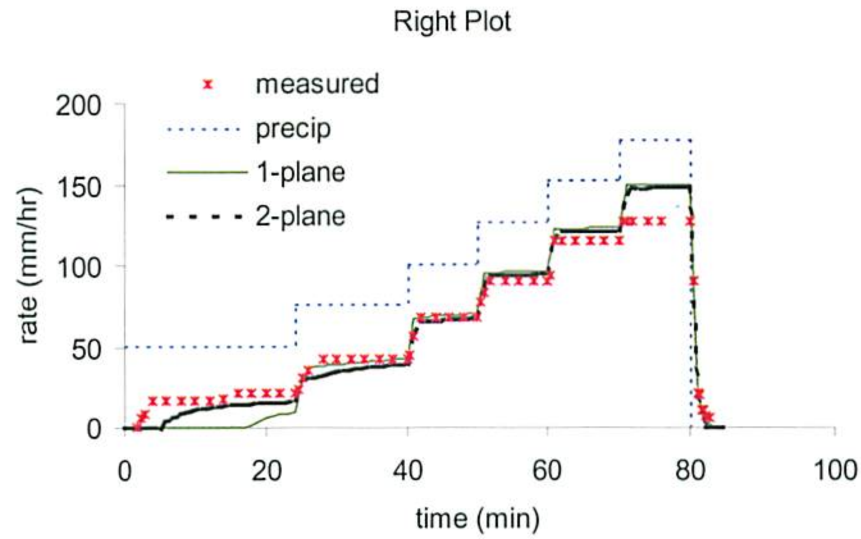


Fig. 5. Comparisons of measured and predicted hydrographs using the one and two plane configurations for the two plots from a continuous simulator run. For the Left Plot, the 1-plane results are completely overlain by the 2-plane results.

The results for the left plot for the two-plane configuration were exactly the same as the single plane results. However, there was an improvement in the ability to match the observed hydrograph from the right plot using the two-plane configuration. In this case, the model did a better job at matching the observed hydrograph at the low intensities. However, the 2-plane model still significantly overestimated the runoff rate at the highest intensity. The fact that the infiltration rate for the Mixed soil changed with intensity made it impossible to accurately model the hydrologic response from the plots using a single K_e parameter for the Mixed soil. Separating out the Bernardino soil on the right plot improved our ability to model the response; however, the behavior of the Mixed soil made it impossible to fit the hydrograph. To model the observed response from either of the two plots, the spatial distribution of the effective hydraulic conductivity within the Mixed soil sites is needed.

Discussion and Conclusions

Initial evaluation of the soil box infiltration experiments indicates that there are many factors that are possibly contributing to the variability of the hydrologic responses of the soils. The objectives of the study were to 1) determine the importance of relative locations of higher and lower infiltration capacity on runoff response and 2) determine how, and if, the relationship between hydrologic response and soil location on the flow plane change with variable rainfall intensity.

The study showed that the location of areas with higher or lower infiltration capacities does have an important effect on runoff response and that the response changes with changes in rainfall intensity. For the two-soil configuration, there were differences in plot response due to the locations of areas of higher or lower infiltration capacity. The right plot, with the Bernardino soil below the Mixed soil, consistently had a higher runoff response than the left plot. Because of the heterogeneous nature of the Mixed soil it was hard to evaluate the effects of run-on run-off processes on either the left or the right plots.

The effect of the rainfall intensity on infiltration and runoff response was more significant for the Mixed soil than for the Bernardino. For the Mixed soil, the infiltration rate increased as the rainfall rate increased which is an indication of partial area response. It was not apparent from the data if the final infiltration rate of the soil had been reached at the highest rainfall intensity applied. For the Bernardino soil, the final infiltration rate was reached at moderate rainfall intensities, indicating that the runoff contributing area was not changing with rainfall intensity.

The implications of these results were demonstrated by applying a distributed runoff model, KINEROS, to the data. Given the increasing infiltration rate with increasing rainfall, it was not possible to accurately simulate a hydrograph for the Mixed soil with variable rainfall intensity using a single value of K_e. However, a single K_e value for the Bernardino soil resulted in a good fit of the hydrograph generated by variable rainfall. Modeling the two-plane configuration as a single plane resulted in a significant over-estimation of the peak runoff from both of the plots at the high intensity and an under-prediction at the low intensity. Using the two-plane configuration did result in an improvement of the ability to match the observed runoff on the right plot. However, there was no difference in the model results from the single plane and two-plane configurations for the left plot. The heterogeneous nature of the Mixed soil made it impossible to accurately model the infiltration and runoff response from either of the two-plane plots even using a distributed process based model. To accurately model the hydrologic response of the Mixed soil and the two plots, the spatial distribution of the effective hydraulic conductivity within the

Mixed soil would have to be determined and the plots would have to be modeled using a more complex configuration.

The soil box used in this study is a simplified model of the complexity that characterizes rangeland watersheds. In this case, the heterogeneity of the soils and the variable precipitation defined the complexity of the system. On natural hillslopes, the complexity of the system is often defined by the spatial variability of the vegetation and cover characteristics and the micro topography. These factors often lead to heterogeneity in the infiltration capacity of an area. The ability to model this complexity at plot and hillslope scales would improve our ability to monitor and manage our rangeland watersheds. To model these complex systems, we need to determine a method to model the partial area response of an area and its change with rainfall intensity.

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