Variable Rainfall Intensity Rainfall Simulator Experiments on Semi-arid Rangelands

Jeffry Stone, Ginger Paige

Abstract

Most rainfall simulator experiments have used a constant rainfall intensity in their experimental design. However, when multiple intensities are used, the steady state infiltration rate tends to increase with increasing rainfall rate, indicating that runoff contributing area is a function of rainfall intensity. Hydrologic data from soil vegetation complexes (Ecological Sites) in Arizona and Mexico suggest that at typical rainfall simulator rainfall intensities, not all of the area is contributing to runoff with the effect being greater for coarse textured soils. Erosion data from similar Ecological Sites indicate that deposition can be a significant component of the total detachment on uniform slopes when microterraces are present. Variable intensity rainfall simulator experiments are necessary to understand and predict small scale hydrologic and erosion processes that may be important in evaluating the sustainability of rangeland hillslopes.

Keywords: runoff, erosion, plots, rainfall simulation

Introduction

Rainfall simulator experiments on rangelands have been conducted since the 1930s to investigate fundamentals of the rainfall/runoff/erosion process and the impacts of grazing management and land characteristics on these processes. Rainfall simulation provides a relatively easy and economical way of obtaining a large amount of data under controlled conditions in a short period of time. In addition, controlled application rates allow for the comparison of steady state infiltration response to alternative management systems, to differences in vegetation and soil characteristics, and facilitates model parameter identification.

The majority of rainfall simulator experiments on rangelands have used a constant application rate in the experimental design. At the Walnut Gulch Experimental Watershed (WGEW), the first rainfall simulator experiments used constant intensities of 100 mm/hr (Kincaid et al. 1964) and 45 mm/hr (Tromble et al. 1974). In the 1980's a series of experiments were conducted on 3 x 10.7 m plots using the Rotating Boom rainfall Simulator (RBS) (Swanson 1965) to parameterize the Universal Soil Loss Equation (USLE) (Simanton and Renard 1985) and Water Erosion Prediction Project (WEPP) model (Simanton et al. 1991). The USLE experimental design consisted of three simulation runs, a dry run of one hour, and 24 hours later, a wet and very wet run both for 30 minutes on three treatments, natural, clipped, and bared. The water application rate for all runs was 60 mm/hr. The WEPP experimental design added 0.75 m^2 bared plots for infiltration parameterization, two water application rates to the very wet run (60 and 120 mm/hr), and multiple overland flow rates introduced at the top of the bare plots. Although the variable flow rates were used for WEPP rill erosion parameter identification on the bared plots, the constant intensity wet run was used for parameterizing the effective hydraulic conductivity term, K_e (mm/hr), of the WEPP infiltration model, the Green-Ampt Mein-Larsen (GAML) equation (Mein and Larsen 1973).

With the introduction of multiple application rates, it was observed that the steady state infiltration rate tended to be higher at higher application rates. In Figure 1, rainfall, observed and predicted infiltration

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curves and hydrographs from the RBS experiment are plotted for a multiple intensity simulation run on a sandy loam soil. The observed steady state infiltration rate, f obs, was computed as the difference between the application rate and the runoff rate at steady state. The predicted infiltration curve, f pred, was computed by adjusting the GAML K_e until the computed runoff volume matched the observed. The predicted hydrograph, q pred, was computed using the IRS model (Stone et al. 1992) which routes rainfall excess using a method of characteristics solution of the kinematic wave equations. Note that the observed infiltration rate, f obs, varies with rainfall intensity and is higher at the higher rainfall rate while the fitted infiltration curve does not duplicate the observed infiltration response. The result of under predicting the infiltration rate at the higher application rate is over prediction of the peak discharge rate.

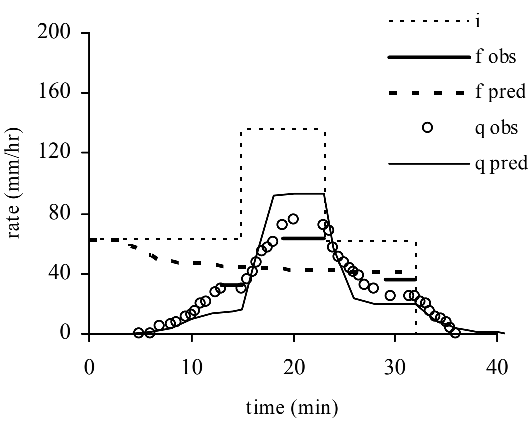

Figure 1. Example of observed and predicted hydrograph and infiltration by fitting the GAML model to runoff volume.

A proposed explanation for the increase in infiltration rate with increasing water application rate shown in Figure 1 is that there is a non-uniform distribution of infiltration capacity over an area such that portions of the area have higher infiltration capacities than other portions. The distribution of infiltration capacity is hypothesized to be caused by the spatial variation of soil and vegetation characteristics over the area. At the lower application rates, only those areas that have an infiltration capacity lower than the application rate will contribute to runoff. As the application rate increases, more of the area that has higher infiltration capacity contributes to runoff. Because of this, the infiltration rate computed as the difference between the application rate and steady state runoff increases.

Hawkins (1982) suggested a relationship between the infiltration rate, $f_s(i)$ (mm/hr), and application rate, i (mm/hr), assuming an exponential distribution of infiltration capacity over an area as

$$f_s(i) = u_f \left(1 - e^{-\frac{i}{u_f}} \right) \tag{1}$$

where u_f (mm/hr) is the average aerial infiltration rate when the entire area is ponded. For Equation 1, the fraction of the area, $A_c(i)$, contributing to runoff for a given rainfall intensity is the cumulative density function of the exponential distribution or

$$A_c(i) = 1 - e^{-\frac{i}{u_f}} \tag{2}$$

The purpose of this paper is to examine the relationship between infiltration rates and rainfall intensity using data collected on soil vegetation complexes or Ecological Sites (ES) and to discuss the implications for runoff and erosion studies.

Methods

The data used for this paper are from two separate experiments, one using the RBS and one using the Walnut Gulch Rainfall Simulator (WGRS) developed by Paige et al. (in review). The WGRS is an oscillating boom simulator that uses the same nozzle, the VeeJet 80100, as the RBS and can apply water at variable intensities in user defined increments ranging from 12 to 177 mm/hr. Both experiments were conducted on similar ESs. The ES is the basis of a land classification scheme used by the Natural Resources Conservation Service (NRCS) in rangeland assessment and planning. The ES is defined by the National Range and Pasture Handbook (USDA NRCS 1997) as "...a distinctive kind of land with specific physical characteristics that differs from other kinds of land in its ability to produce a distinctive kind and amount of vegetation."

Study areas

Five ESs located at the WGEW and in Chihuahua, Mexico were used for the RBS experiments; Sandy Loam Upland (SLU), Loamy Upland (LoU), Limey Slopes (LS), Limey Upland (LiU), and Clay Loam Upland (CLU). All of the soils were sandy to gravely sandy loams with the exception of the CLU ES that was a clay loam. The LS ES was brush dominated with no grazing and the remainder of the ESs had primarily grass vegetation with various levels of grazing intensity. The SLU ES had three separate locations with the ecological status ranging from fair to excellent and the CLU ES had two locations ranging from poor to excellent. All of the plots were 3 x 10 m and consisted of a natural treatment.

Two ESs at WGEW and at The Research Ranch (TRR) near Elgin, AZ were used for the WGRS experiment. All of the plots were 2 x 6 m and consisted of two treatments, natural (LoU-n and LS-n) on the WGEW and burned (LoU-b and LS-b) on The Research Ranch. The dominant vegetation at all of the sites was grass (pre-burn for LoU-b and LS-b) in good to excellent ecological condition. See Table 1 for additional characteristics of the ESs for both experiments.

Table 1. The range of canopy cover, CC, ground cover, GC, and average slope for the Ecological Sites.

ES	n[1]	CC (%)	GG (%)	Slope (%)
SLU	11	29-78	57-89	8
LiU	2	52	83	9
LS	2	34	84	11
LoU	4	17-46	26-51	11
CLU	8	23-31	31-39	3
LoU-n	2	88	82	8
LoU-b	2	0	73-29[2]	8
LS-n	3	64	60	11
LS-b	2	0	76-58	12

[1] number of plots, [2]pre and post simulation.

Experimental design

The RBS experimental design was similar to the WEPP design with the exception that three intensities were applied for the very wet run on some of the plots. For the WGRS experiment, the simulation run sequences were a 45 minute constant intensity run at 60 mm/hr followed one hour later by a variable intensity run. For the variable intensity run, the rates were changed after runoff had reached steady state for at least five minutes.

For both experiments, a flume was used to measure runoff depth from the plot that was converted to discharge using a pre-calibrated stage-discharge relationship. Rain intensity for the RBS was measured by a weighing bucket recording raingage and adjusted for wind effects by six non-recording rain gages distributed on the plot. Rain intensity for the WGRS was obtained through calibration and wind effects were minimized through the use of wind screens on the simulator. Canopy and ground cover were measured using a point frame at 490 points for the RBS experiment and 390 points for the WGRS experiment. Canopy cover was recorded as grass, shrub, or forb and ground cover was recorded as rock (>2 mm), litter, vegetative base, and bare soil. Ground cover was measured both outside and inside canopy cover. For the LoU-b and LS-b, cover was measured before and after simulation.

The RBS very wet run data were used to parameterize u_f in Equations 1 and 2 because the data represented a wide range of soils, vegetation composition, and ecological status. The WGRS multiple intensity data were used to examine the erosion response because of the large differences in canopy and soil surface characteristics caused by the burn treatment.

Results

RBS experiment

Plotted in Figure 2a are the f_s-i curves generated by manually optimizing for u_f in Equation 1 and the average and range of u_f are listed in Table 2. For the SLU ES, $f_s(i)$ of some of the simulator plots did not reach a final value at the highest rainfall intensity while for the CLU, a final value was reached at the lowest intensity for all the plots. The variability of u_f within an ES was greater than the variability among ESs. Using the criteria of no overlap of the ranges of u_f, the SLU, LoU, and CLU ESs are different while the LiU ES was similar to the SLU ES and the LS ES was similar the LoU ES.

Table 2. u_f values for the f_s-i relationship.

ES	u_f (mm/hr) average	u_f (mm/hr) range
SLU	82	50 - 130
LiU	57	55 - 75
LS	30	30
LoU	28	18 - 45
CLU	10	10

The range of runoff contributing area or partial area response, $A_c(i)$, with intensity was calculated using Equation 2 with the range of u_f in Table 2 and is plotted in Figure 2b. Referring to Table 3, at the lower intensity of 60 mm/hr, the partial area response is significant for the SLU ($A_c(i)$ = 0.38-0.70), LiU

($A_c(i)$ = 0.55-0.65), and portions of the LoU. At the higher intensity of 150 mm/hr, although most of the ESs have 90% or greater of the area contributing to runoff, some of the SLU and LiU plots still have less than 90% area contributing to runoff.

Table 3. Lower and upper limits of runoff contributing area, $A_c(i)$, for 60 and 150 mm/hr rainfall intensity using the range of u_f from Table 2 with Equation 2.

ES	A_c(60 mm/hr)		A_c(150 mm/hr)	
	Lower	Upper	Lower	Upper
SLU	0.38	0.70	0.70	0.95
LiU	0.55	0.65	0.86	0.93
LS	0.86		0.99	
LoU	0.74	0.96	0.96	1.00
CLU	1.00		1.00	

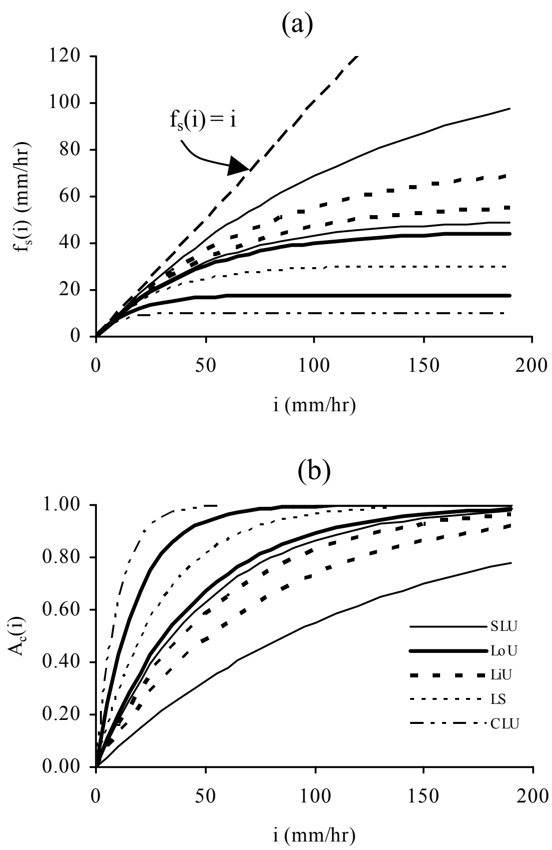

Figure 2. a) f_s-i relationship and b) contributing area for selected Ecological Sites in MLRA 41.

Using total ground cover, gc (%), in a regression with u_f, an exponential model proved to be the best fit and the following equation was obtained

$$u_f = 13.2\, e^{0.024\, gc} \quad R^2 = 0.66 \quad SE = 24.3 \qquad (3)$$

where R^2 = coefficient of determination and SE = standard error (mm/hr). For comparison purposes, the GAML K_e parameter was computed for the same data set and the following regression equation was obtained

$$K_e = 13.5\, e^{0.013\, gc} \quad R^2 = 0.44 \quad SE = 10.0 \qquad (4)$$

The data points and Equations 3 and 4 are plotted in Figure 3. Although there is a fair amount of scatter for both parameters, the similarity between the intercepts
in Equations 3 and 4 implies that u_f is a conductivity term. The intercept is the bare soil value of the parameter and can be interpreted as a textural based conductivity that is modified for cover. The intercept value of 13 mm/hr is very close to the IRS model's (Stone et al. 1992) default bare soil saturated hydraulic conductivity of 10 mm/hr for a sandy loam based on Rawls et al. (1982). The positive correlation with ground cover suggests an interpretation of Figure 2a. As ground cover increases, u_f increases and higher rainfall intensities are required for the entire area to contribute to runoff. For an individual ES, the shape of the curves in Figure 2a may be an indicator of hydrologic condition with the flatter the curve, the poorer the hydrologic condition.

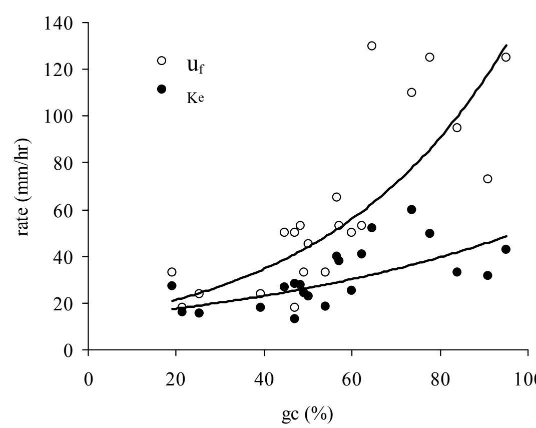

Figure 3. Relationship between ground cover, gc, and K_e and u_f.

WGRS experiment

The burned treatment was the result of a low to moderate severity wildfire that burned all the vegetation at TRR. Litter and ash from the fire made up a major portion of the ground cover. From observations during the burned plot simulations, litter was transported off the plot by overland flow or formed litter dams behind flow obstructions caused by rocks or vegetative bases. This process was dynamic, with the dams forming during the lower runoff rates of the dry and wet runs and being breached at the higher rates. After a dam was formed, sediment was deposited upstream from the dam creating a microterrace. When the dam was breached during the higher runoff rates, the runoff began to erode the microterrace much like a headcut. The geometry and number of microterraces on several of the plots was used to compute an estimate of deposited sediment. According to these calculations, about 40% of the detached soil was deposited on the LS-b plots and about 80% on the LoU-b plots. Although these estimates are very rough due to uncertainty of the initial microtopography, they do suggest that deposition of sediment on these sites is a significant component of the erosion process and that the microterraces had an ameliorating effect on the total sediment yield.

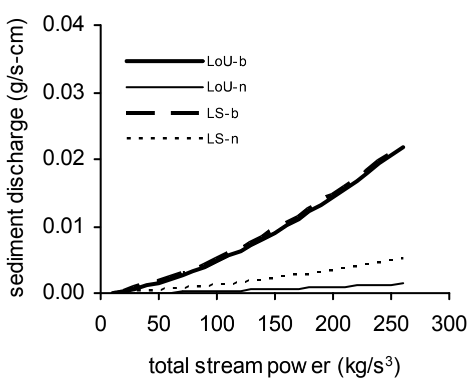

Figure 4. Steady state sediment discharge rate versus total stream power.

The dynamic nature of the erosion process was more dramatic at the burned sites but was also present at the unburned sites. As an illustration, steady state sediment discharge, q_s (g/s-cm) is plotted versus total stream power, ω (kg/s^3) in Figure 4 for the two treatments on the two ESs. Stream power is computed as ρ gqS where ρ = density of water (kg/m^3), g = gravitational constant (m/s^2), q = unit discharge (m^2/s), and S_0 = average plot slope (m/m). There was a very strong log-log relationship between q_s and ω for both the burned and unburned plots with coefficients of determination all greater than 0.85. The two burned treatments had very similar relationships and notably higher sediment discharge rates at the same stream power when compared to the unburned treatments.

Discussion and Conclusions

The vast majority of rainfall simulator experiments have used a single application rate as part of the experimental design. For example, Alberts et al., (1995) used the wet run with a 60 mm/hr application rate from the WEPP field experiment to parameterize K_e. However, as shown in Figure 2b, for ESs with coarse texture surface soils, one rate does not ensure that the entire plot is contributing to runoff. In the case of parameterizing K_e, if A_c(i) is not known a priori, then the selection of a single application rate is arbitrary and the resulting parameter value may not fully describe the hydrologic response of the site. A single application rate may also lead to mis-interpretation of results or incorrect relationships between hydrologic variables and plot characteristics. Under partial area response, local rates and amounts of runoff and erosion and hydraulic parameters such as flow shear are underestimated if the entire plots is assumed to be contributing.

In general, erosion models do not account directly for the influence of microtopography on detachment and deposition nor will they compute deposition on a uniform slope. Although the formation of microterraces on the burned plots occurred within the duration of the simulation experiment, their influence on sediment yield appeared to be significant. Preliminary studies on the characteristics of microterraces on the LoU-n and LS-n ESs suggest that these features make up from 30-50% of the hillslope microtopography. The rate at which microterraces form and how they affect both the runoff and erosion processes on unburned areas is largely unknown. Variable intensity rainfall simulator experiments should give insight into these processes. For example, from observations during the lower application rates at the burned sites, water ponded on the microterraces behind the litter dams while water did not pond on the sloping non-microterrace areas. Future experiments are planned using tracers to quantify how different hillslope microtopographic areas respond at different rainfall intensities.

The hydrologic indicators of the multi-agency rangeland health evaluation (Pyke et al., 2002), such as water flow paths, the presence of erosional pedestals and microterraces, can be interpreted as qualitative descriptors of partial area processes. In order to quantify and model hydrologic and erosion processes and their effects on the sustainability of an ecosystem, it will be necessary to define hydrologic relationships such as the f_s-i relationship described in this paper.

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