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EFFECT OF SLOPE ON RUNOFF FROM A SMALL VARIABLE SLOPE BOX–PLOT

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*Many factors affect catchment hydrologic characteristics, which also ultimately influence the production of surface runoff. This study evaluated the effect of slope on infiltration and surface runoff from a variable-slope box under artificial rainfall simulation. The variable-slope box consisted of 0.25 m deep Captina silt loam soil (fine-silty, siliceous, active, mesic Typic Fragiudult) seeded to tall fescue (*Festuca arundinacea *Schreb.); rainfall simulations were conducted on 11 slopes (0, 1, 2, 4, 6, 8, 10, 15, 20, 25, and 28%). The rainfall simulations were about 20-min long at 5-cm* hr^{-1} *because initial results showed that runoff occurred after 5-min, and we wanted about 15-min of continuous runoff for this investigation. The variable-slope box demonstrated the effect of slope on infiltration rate and surface runoff production, where surface runoff volume increased with the natural logarithm of slope (%slope plus 0.1). However, the effect of slope was almost precluded by variability in surface runoff production probably resulting from variation in the antecedent soil moisture of the variable-slope box. The variations in antecedent moisture were likely related to the change in ambient air temperature occurring with time and natural rainfall during late fall. It may be that slope of the infiltrating surface has the greatest effect on surface runoff production when the soil is closer to saturation. The effect of slope on infiltration and surface runoff production needs additional investigation where antecedent soil moisture conditions would be measured spatially within the variable-slope box.*

INTRODUCTION

The major abstraction from rainfall during surface runoff producing events is infiltration, which is a complex process with spatial and temporal variability (Horton, 1933; Haan et al., 1994). In general, the infiltration rate is dependent upon several soil properties and site characteristics that will ultimately affect surface runoff production from the landscape. These soil properties and site characteristics are often intimately connected where one property influences another property. The most common soil properties affecting infiltration, and thus surface runoff production, are bulk density, degree of structure or aggregation, presence of macropores and saturated hydraulic conductivity. The presence of coarse fragments in soils may also influence infiltration and surface runoff production (Sauer and Logsdon, 2002). The most common site characteristics affecting infiltration are vegetative cover, grazing conditions (see Gifford and Hawkins, 1978), slope of the infiltrating surface, and subsurface conditions in the upland (Bras, 1990). Spatial variation of meteorological conditions, soil hydraulic properties, ground water depth, and other site characteristics influences surface runoff production and location with which surface runoff occurs across the landscape (e.g., see Betson, 1964; Gburek and Sharpley, 1998; Pionke et al., 1997).

Of these site characteristics, this investigation focused on the effect of slope on infiltration rate and surface runoff production. Some previous studies have investigated the effect of slope on surface runoff production, sediment transport and nutrient loss (Ahuja et al., 1982; Barros et al., 1999; Everett and Dutt, 1985; Naslas et al., 1994) where surface runoff often increased as slope increased. Many studies have also looked at the effect of slope length on soil erosion (e.g., Gilley et al., 1987; Liu et al., 2000; Truman et al., 2001). Catchment slope influences runoff in stream networks, probably because steeper slopes produce more runoff or mountainous regions with steeper slopes have more precipitation (Dodds, 1997). Despite these observations, soil or field slope is often not a sensitive hydrologic parameter in many hydrologic simulation models with regard to surface runoff generation; field slope may be very important when evaluating the risk of nutrient loss on a field by field basis. The specific objective of this study was to evaluate the effect of slope from an individual small variable-slope box. A single variable slope box–plot was used where infiltration rate of the soil was constant but antecedent soil moisture conditions likely varied over the experiment.

METHODS

This study evaluated the effect of slope on infiltration and surface runoff from a variable-slope box under artificial rainfall (Figure 1). The variable-slope box dimensions were 1.5-m wide, 3-m long and 0.5-m depth. The inside of the box was lined and filled with gravel to 0.05-m from the bottom of the variable-slope box and then with sand to a depth of 0.25-m from the bottom of the box. Approximately 0.25-m of disturbed Captina silt loam soil (fine-silty, siliceous, active, mesic Typic Fragiudult) was placed above the gravel and sand, and tall fescue (*Festuca arundinacea* Schreb.) was seeded and fertilized with poultry litter in fall 2000 and reseeded in spring 2001. An aluminum (Al) trough was used to collect surface runoff at the downslope end of the variable-slope box. Subsurface flow was defined as the leachate collected through a hole approximately 0.05-m from the bottom ofthe box at the downslope end. The variable-slope box received artificial rainfall at a rate of 5-cm hr^{-1} from two nozzles (TeeJet 1/2HH-SS30WSQ, Spraying Systems, Wheaton, Illinois, USA) set approximately 3 m above the soil surface. These same nozzles have been used in many rainfall simulation studies (e.g., see DeLaune et al., 2004; Haggard et al., 2005; Smith et al., 2004), and the coefficient of uniformity was greater than 0.8 at all slopes when evaluated in trial rainfall simulations (data not shown).

Figure 1. Picture of the variable slope box-plot located at the poultry farm on the University of Arkansas Agricultural Experiment Station, Fayetteville, Arkansas.

In fall 2001, rainfall simulations were conducted on the variable-slope box; three rainfall simulations were conducted on the following 11 slopes: 0, 1, 2, 4, 6, 8, 10, 15, 20, 25, and 28%; the variable slope box–plot tilted along the long axis. Rainfall simulations generally occurred on every other day from 11 September through 6 December, although natural rainfall events sometimes delayed the artificial rainfall simulations. The slope was adjusted by elevating the up-slope end of the variable-slope box, and slopes used in the artificial rainfall simulation were sequenced randomly within three groups, i.e. each slope was used once per group or block over time. The rainfall simulations were 20-min long at 5-cm hr^{-1}; initial trials showed that runoff occurred after 5-min and about 15-min of continuous runoff was desired for this investigation. During the artificial rainfall simulations on the variable-slope box, time to surface runoff and subsurface flow were recorded. Runoff rates and volumes were recorded manually by measuring the weight of water over time. Electrical conductivity (Thermo Orion Model 105A+ Conductivity Meter, Waltham, MA) and pH (OakTon pHTestr 3, Vernon Hills, IL) were measured on the collected surface runoff and subsurface flow. Water-quality samples were collected from surface runoff and subsurface flow, and 20 mL was filtered through a 0.45 mm membrane then acidified to around pH<2 using concentrated HCl. The acidified filtrate was analyzed for dissolved reactive phosphorus (DRP) using the automated ascorbic acid reduction method (APHA, 1992). Mean daily air temperature (°C) was obtained from the University of Arkansas Agricultural Experiment Station.

RESULTS AND DISCUSSION

Effect of Time

Some differences in ambient mean daily air temperature occurred across the treatment groups where group 1 generally had highest mean air temperature (20.1±2.8°C) and group 3 the lowest mean air temperature (10.5±5.1°C); the mean air temperature during group 2 was 15.2±3.6°C. This observation is not surprising given the timeframe with which each treatment group occurred: group 1 (11 September through 25 September 2001); group 2 (26 September through 7 November 2001); and group 3 (8 November through 6 December 2001). These changes in temperature likely contributed to variation in antecedent moisture conditions and surface runoff response of the variable-slope box across the treatment groups (i.e., time).

The amount of surface runoff significantly varied between treatment groups, increasing from an average of 0.07-cm in group 1 to 0.68-cm in group 3; average runoff from group 2 was 0.16-cm (Figure 2). The variability in surface runoff production within each treatment group also increased with time but the coefficient of variability was not consistent across treatment groups (group 1: 71%; group 2: 75%; group 3: 31%). This variability was due to greater antecedent soil moisture from less evapotranspiration from the variable-slope box as temperature decreased with time (i.e., across treatment groups) and also natural rainfall events that typically occur in the fall. In contrast, the amount of subsurface flow did not increase across treatment groups, but there was some variation.

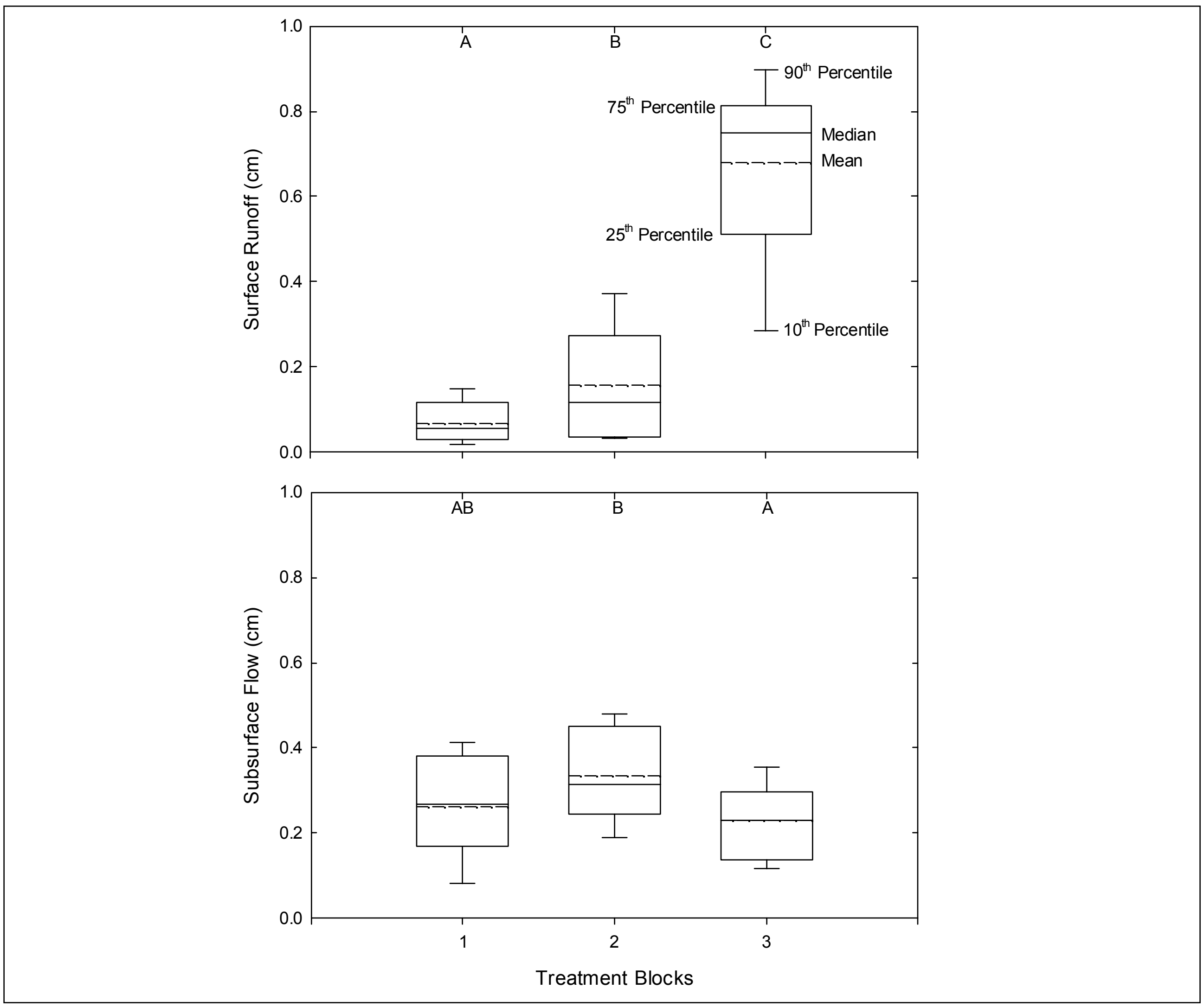

Figure 2. Box plots of surface runoff and subsurface flow across the three treatment groups during the variable-slope box study. [Different letters across the top of each graph indicate significant differences in treatment groups using Analysis of Variance (ANOVA) of natural logarithm (ln) transformed data at a = 0.10.]

The amount of total runoff volume from the variable-slope box (surface runoff plus subsurface flow) changed across treatment groups, similar to surface runoff.

The changes across treatment groups are likely representative of changes in regional air temperatures and antecedent soil moisture conditions which are present across the rainy seasons in northwest Arkansas, where group 1 would represent relatively warm, dry conditions and group 3 would represent relatively cold, wet conditions. These differences among treatment groups add to the robustness of this study, demonstrating the average effect of slope on surface runoff and other parameters across a variety of environmental and antecedent moisture conditions.

Effect of Slope

The time to surface runoff ($Time_{RO}$) was generally not influenced as slope increased on the variable-slope box; however, $Time_{RO}$ was usually lower at the greater slopes. When only slopes from 1 to 28% were used in simple linear regression, a marginally significant relationship existed between slope and $Time_{RO}$ ($Time_{RO}$=-0.57·ln(%Slope+0.1)+7.16, R^2=0.30, p=0.10). Similarly, the time to subsurface flow ($Time_{SF}$) decreased as the slope of the variable-slope box increased ($Time_{SF}$=-1.10·ln(%Slope+0.1)+18.04; R^2=0.44; p=0.03), where slope explained 44% of the variability. Mean $Time_{RO}$ at each slope across the treatment groups was consistently less than $Time_{SF}$ (Table 1). The time to surface runoff and subsurface flow was variable, particularly betweentreatment groups where mean $Time_{RO}$ and $Time_{SF}$ decreased from 6.6 (group 1) to 5.1 min (group 3) for surface runoff and from 17.8 to 17.3 min for subsurface flow. The three-fold difference in $Time_{RO}$ and $Time_{SF}$ demonstrates that movement of the artificial rainwater did not flow preferentially through macropores or along the sides of the variable-slope box.

Table 1. Effect of Slope on Time to Surface Runoff ($Time_{RO}$) and Subsurface Flow ($Time_{SF}$), pH of Surface runoff (pH_{RO}) and Subsurface Flow (pH_{SF}), and Electrical Conductivity of Surface Runoff ($Cond_{RO}$) and Subsurface Flow ($Cond_{SF}$) at Each Slope Used in this Variable-Slope Box Study, Summer and Fall 2001

Slope*	**$Time_{RO}$** (min)	**$Time_{SF}$** (min)	**pH_{RO}**	**pH_{SF}**	**$Cond_{RO}$** (μS cm^{-1})	**$Cond_{SF}$** (μS cm^{-1})
0	6.30	19.10	7.58	7.09	322	529
1	7.03	21.53	7.67	7.40	356	543
2	7.38	17.47	7.55	7.09	293	504
4	5.04	15.24	7.86	7.20	283	528
6	6.54	17.24	7.77	7.18	294	537
8	4.86	11.22	7.39	7.10	307	521
10	7.71	17.47	7.82	7.18	330	531
15	5.93	15.01	7.51	7.07	368	552
20	5.13	15.37	7.75	7.08	277	465
25	4.58	14.38	7.82	7.01	278	478
28	5.64	14.13	7.88	7.05	331	489

*Data represents the mean of three values at each slope across the treatment groups.

The infiltration capacity of the variable-slope box can be determined from the difference between rainfall rate and runoff rate assuming surface storage is minimal at 0% slope. The infiltration rate of the box was 4.7-cm hr^{-1}, representing almost 94% of the simulated rainfall rate (5-cm hr^{-1}); thus, very low runoff volumes would be expected if infiltration excess controlled surface runoff. However, it was apparent that surface storage at 0% slope was significant because at 1% slope the runoff volume almost doubled. At 1% slope, the infiltration rate of the box was approximately 4.5-cm hr^{-1}, representing 89% of the simulated rainfall rate. Thus, the actual infiltration rate of the variable-slope box is likely between 4.5 and 4.7-cm hr^{-1}.

Slope significantly affected the volume of surface runoff from the variable-slope box (Figure 3); other studies have shown similar responses to slope (e.g., see Barros et al., 1999). The relationship between surface runoff and slope increased in a nonlinear fashion (RO_{cm}=0.06×ln(%Slope+0.1)+0.22; R^2=0.89; p<0.0001). The maximum average amount of runoff (0.43-cm) was measured at the maximum slope (28%) where the infiltration rate was approximately 74% of the simulated rainfall rate at this slope. However, the natural logarithmic relation between surface runoff and slope suggested that surface runoff production would continue to slightly increase at slopes greater than 28%.

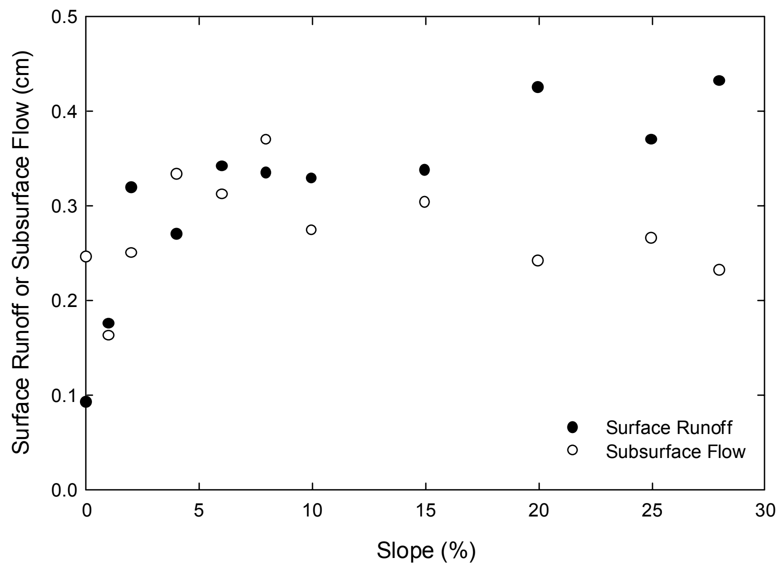

Figure 3. Effect of soil slope on surface runoff and subsurface flow from a variable-slope box receiving rainfall at a rate of 5-cm hr^{-1} for 20-min (symbols represent mean of the values at each % slope across treatment groups).

This study showed that slope significantly affects surface runoff generation when holding almost all other parameters constant, except temperature and therefore antecedent moisture. On a larger perspective, a weak, but significant, relationship has been observed between catchment slope and annual runoff (Dodds, 1997). The slope of the infiltrating surface not only increases surface runoff, but potentially increases dissolved phosphorus (P) concentrations in surface runoff (Ahuja et al., 1982). However, the current study did not observe any relationship between dissolved P concentrations in surface runoff and the slope of the infiltrating surface (Figure 4). Dissolved P concentrations in the subsurface flow decreased with increasing slope (SRP_{SF}=-0.005×%Slope+0.287; R^2=0.54, p=0.01) but were not significantly related to subsurface discharge. In contrast, mass P loss in surface runoff displayed a significant natural logarithmic relationship with box slope ($Ploss_{RO}$=0.96×ln(Slope+0.1)+2.46; R^2=0.61; p<0.01) whereas mass P loss in subsurface flow was not related to slope of the infiltrating surface. Mean P concentrations in surface runoff (0.24-0.36 mg SRP L^{-1}) and subsurface flow (0.22-0.28 mg SRP L^{-1}) did not significantly change between treatment groups (i.e., over time), suggesting that P transferred in runoff water was not depleted in this box study.

Physicochemical data also provided some evidence that the artificial rainwater that did not runoff infiltrated the soil surface, and percolated through the soil box. Electrical conductivity was less in surface runoff than subsurface flow, whereas pH was greater in surface runoff than subsurface flow (Table 1). Dissolved P concentration was also generally less in surface runoff compared to that measured in the subsurface flow especially at the slopes greater than 5% (see Figure 4). These differences in physicochemical parameters indicate that the infiltrating water had sufficient time to interact with the soil and alter its properties.

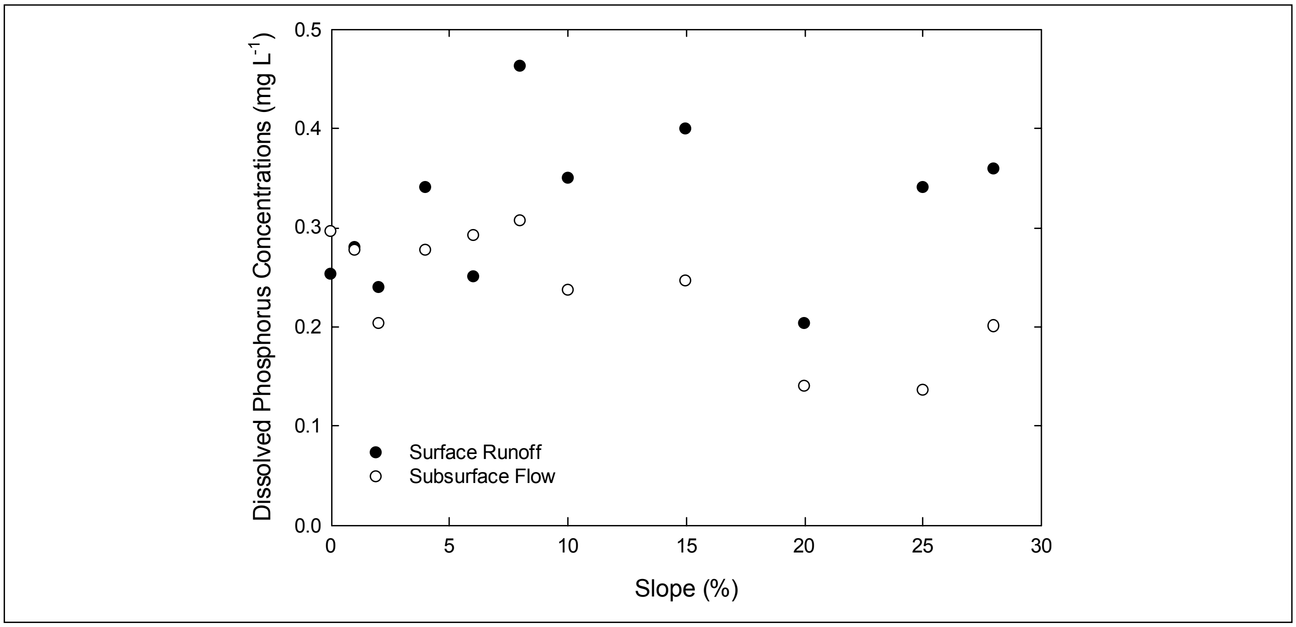

Figure 4. Effect of soil slope on dissolved phosphorus concentrations in surface runoff and subsurface flow from a variable-slope box receiving artificial rainfall at a rate of 5-cm hr^{-1} for 20-min (symbols represent mean of the values at each % slope across treatment groups).

CONCLUSION

The variable-slope box demonstrated a significant effect of slope on infiltration rate and surface runoff production, where surface runoff increased with the natural logarithm of slope (%slope plus 0.1). The effect of slope was almost precluded by variability in surface runoff production, probably resulting from variation in the antecedent soil moisture of the variable-slope box. The variations in antecedent moisture were likely related to the change in ambient air temperature occurring across treatment groups and natural rainfall during late fall. However, these variations in environmental and antecedent conditions across the treatment group make the observed relationship between slope and surface runoff more robust and representative of the average effect across seasons in this region. It may be that slope of the infiltrating surface has the greatest effect on surface runoff production when the soil is closer to field capacity and even saturation. Although dissolved P concentrations in surface runoff were not related to slope or surface runoff, mass P loss increased with slope in a fashion similar to surface runoff suggesting that slope influences P loss through increased surface runoff.

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