Length and Slope Effects on Runoff from Sodium Dispersed, Compacted Earth Microcatchments[1]

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ABSTRACT

The effects of microcatchment slope and length on runoff and erosion rates were studied under 18 rain storms to get information for design of water harvesting systems. Two replicates of a two-factor experiment, including 1, 5, 10, and 15% slopes and 3-and 6-m lengths, were built on a gravelly sandy clay loam (mixed mineralogy) using 11.2 t ha^{-1} of NaCl mixed into the surface 2 to 5 cm of soil followed by compaction with a 6-t roller after a heavy rain. Both slope and length had effects on runoff significant at the 0.1% probability level but the effect of rainfall intensity was not significant. The best fit linear model of runoff, Q, (cm) vs. rainfall, P, (cm) was $Q = 0.858(P - 0.34)$ which explained about 98% of the variability in runoff on individual plots for individual storms but which explained no differences in runoff among treatments. A nonlinear model incorporating slope, s, (m/m) and length, x, (m) accounted for about 96% of the variability in average total runoff among treatments. This model, $Q = (s^{0.0453}\, x^{-0.183} + 0.183)(P - 0.339)$, shows that the important differences in runoff among treatments can be explained by slope and length alone for our conditions. Water quality analyses indicated that only a minor salinity problem but slight to moderate permeability problems might be expected. However, no apparent problems have arisen in 12 yr of grape (*Vitis vinifera*) and fruit tree (*Prunis* sp.) cultivation in a water harvesting system using our catchment on the same soil.

Additional Index Words: **linear model, nonlinear model, surface slope, downslope length, microcatchment systems.**

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INCREASING SLOPE and decreasing length of microcatchments often increase runoff (Hollick, 1974a, b; Boers and Ben-Asher, 1979), but agronomic, topographic and climatic factors may limit the choice of length and slope. Many water harvesting catchment surface treatments for increasing runoff have been proposed and tested (USDA, 1975; Dutt et al., 1981) but seldom have the factors of surface slope and downslope length been included in the experimental designs. Also, equations predicting runoff on the basis of both slope and length have not been published for water harvesting catchments although such equations are needed for design purposes.

Early water harvesting researchers often reported results as an "annual runoff percentage" which was defined as the percent of annual rainfall that ran off. Shanan and Tadmor (1979) warned against the use of annual runoff percentage in design of microcatchment systems. Efficient design usually requires that runoff be predictable on a daily rainfall basis. This is especially true where runoff water is stored directly in the root zone, as in some microcatchment farming systems where drought conditions can occur if refill of storage is untimely or inadequate.

A study was conducted on the effects of slope and downslope length on daily runoff and erosion from earthen microcatchments treated with sodium salt and compacted. An earlier paper (Evett and Dutt, 1985) dealt with the erosion aspects; this second part deals with the runoff results.

MATERIALS AND METHODS

The experimental design was described in an earlier paper (Evett and Dutt, 1985). Briefly, 16 2-m wide runoff plots were constructed using the Ap horizon of the White House gravelly sandy clay loam (fine, mixed, thermic Ustollic Haplargids) at the Univ. of Arizona's Oracle Agricultural Center about 36 km north of Tucson, AZ. The two-factor, two replicate experimental design included slopes of 1, 5, 10, and 15% and lengths of 3 and 6 m. The moist soil was compacted with a 6-ton roller after 11.2 t ha^{-1} of NaCl were mixed into the surface 2 to 5 cm of soil. Total runoff was measured volumetrically after each storm. Electrolytic conductivity, EC, and Na content of the runoff were measured and the sodium absorption ratio, SAR, was calculated (Evett, 1983, p. 70–74).

RESULTS

Seven of the 18 storms studied produced no runoff but totaled just 0.7 cm or 4.4% of total rainfall (Evett, 1983, p. 76). The runoff ratio, defined as the decimal fraction of rainfall that ran off, tended to vary directly with rainfall amount, averaging as high as 0.77 for larger rains and as low as 0.08 for smaller rains (Evett, 1983, p. 76). Also, overall runoff ratios increased with plot slope and decreased with plot length (Table 1). Total runoff depths varied considerably among the eight treatments and the differences were directly related to plot length and slope (Table 1). For example, runoff increased by 25%, going from 8.6 cm for the

Table 1. Total runoff depths and overall runoff ratios†, and equations‡ of runoff depth vs. rainfall for each treatment, for 18 rainfall events.

Treatment	Runoff depth, cm	Runoff ratio	Equation	SD	r^2
3 m, 1%	9.6	0.61	$Q = 0.873\,(P - 0.375$ cm)	0.062	0.994
3 m, 5%	10.2	0.65	$Q = 0.904\,(P - 0.348$ cm)	0.053	0.996
3 m, 10%	10.4	0.66	$Q = 0.883\,(P - 0.300$ cm)	0.092	0.987
3 m, 15%	10.9	0.69	$Q = 0.916\,(P - 0.293$ cm)	0.080	0.991
6 m, 1%	8.6	0.55	$Q = 0.768\,(P - 0.348$ cm)	0.079	0.987
6 m, 5%	8.9	0.56	$Q = 0.818\,(P - 0.383$ cm)	0.112	0.978
6 m, 10%	9.5	0.60	$Q = 0.845\,(P - 0.350$ cm)	0.099	0.984
6 m, 15%	9.8	0.62	$Q = 0.852\,(P - 0.325$ cm)	0.163	0.962
Plot length					
3 m			$Q = 0.894\,(P - 0.329$ cm)	0.084	0.989
6 m			$Q = 0.816\,(P - 0.355$ cm)	0.155	0.975

† Average for two replicates except of the 6 m, 15% treatment for which data for one replicate were lost due to a leaky collection basin. Runoff ratio = (runoff depth)/(rainfall depth).

‡ Based on linear regression analysis of 22 data pairs apiece for all treatments except the 6 m, 15% treatment for which only 11 data pairs were available; and, on 88 data pairs for the 3 m plots and 77 data pairs for the 6 m plots.

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6m, 1% to 10.9 for the 3m, 15% treatment, under a total rainfall of 15.8 cm (NOTE: The treatments will be referred to throughout by abbreviations. For example, "6m, 1%" refers to a treatment having 6 m downslope plot length and a 1% slope).

Rainfall-runoff Relationships

If infiltration rates are low, then a model of the form

$$Q = B_1(P - B_2) + \epsilon \qquad [1]$$

can sometimes be usefully fitted to daily rainfall-runoff data, where P is rainfall depth, Q is runoff depth, B_1 is called the runoff efficiency, B_2 is called the threshold rainfall depth, and ϵ is an error term (Evett, 1983, p. 8, 9; Frasier, 1974; Morin, 1977; Myers, 1963). Diskin (1970) showed that inclusion of all data, including zero runoff events, while fitting Eq. [1] tended to give values of B_1 and B_2 that were lower than the true efficiency and threshold values. His two part model:

$$Q = \begin{cases} 0 + \epsilon, & P < B_2 \\ B_1(P - B_2) + \epsilon, & P \geq B_2 \end{cases} \qquad [2]$$

was included in an optimization program, LEGLR, by E.D. Shirley (1982). The computer program began with the setting of an arbitrary value for B_2 and proceeded through a two-step iteration:

1. The sum of squared deviations of runoff values from the line $Q = 0$ was calculated for data pairs for which $P < B_2$, and this sum was added to the sum of squared deviations of runoff values from the least squares linear regression line, $Q = B_1(P - B_2)$ (where B_2 is now fixed), fitted to data pairs for which $P \geq B_2$.
2. The value of B_2 was increased by a small amount and Step 1 was repeated.

Iteration proceeded until the minimum total sum of squares was found and the corresponding values of B_1 and B_2 were taken as the best estimates. These estimates tend to give much better values for runoff efficiency and threshold rainfall than do the least squares regression estimates of B_1 and B_2 from Eq. [1] applied to all of the data (Diskin, 1970; Evett, 1983, p. 8–12).

We used the LEGLR program getting a rainfall-runoff relationship for combined treatments of

$$Q = 0.858(P - 0.340) \qquad [3]$$

where Q and P are in centimeters. Following a suggestion of Frasier (1974) we also used data from all nonzero runoff events to fit Eq. [1] by least squares regression, obtaining the same result as Eq. [3] with $r^2 = 0.976$ and SD = 0.117. Since results of the two methods were the same, we used the simpler method of least squares regression on all nonzero runoff events for subsequent analyses.

Our 3m plots all had higher runoff efficiencies than did 6m plots (Table 1 and Fig. 1). A t-test showed that the runoff efficiency of 0.894 for combined 3m treatments was significantly greater, at the 1% level of probability, than the runoff efficiency of 0.816 for combined 6m treatments. The threshold rainfalls of 0.329 cm and 0.355 cm were not significantly different between the two lengths even at a 10% level of probability of type 1 error. Among treatments, runoff efficiency was significantly different at the 5% level of probability only between the 6m, 1% and 3m, 15% treatments. Threshold rainfall values for any two treatments were not significantly different at the 5% level of probability. The similarity of threshold rainfall values for all treatments is probably due to the smooth plot surfaces formed with the steel drum roller during compaction as well as to the care with which plot grade and surface flatness were established during construction.

Rands (1980) reported a runoff ratio of only 0.33 for a 6.1-m plot at 3% slope built using only compaction on the same soil and within 100 m of the site used for this study. By comparison, the runoff ratios for our 6m, 1% and 6m, 5% treatments were 0.55 and 0.56, respectively (Table 1). Rands' plot also exhibited a lower runoff efficiency at 0.53 and higher threshold rainfall at 0.74 cm (our analysis of Rand's data for non-zero runoff events) than did our 6m, 1% and 6m, 5% treatments which had runoff efficiencies of 0.77 and 0.83 and threshold rainfalls of 0.35 and 0.38 cm, respectively. This is fairly conclusive evidence of the beneficial effects of the NaCl treatment on this soil since Rands' compaction methods were very similar to those used in our study. No control plots (using compaction only) were used in our study since we were interested mainly in studying the performance of the sodium dispersed, compacted earth catchment; not in comparing the sodium dispersion treatment to a compacted earth only treatment.

Predicting Runoff Efficiency

Runoff efficiency increased with plot slope for a given plot length except for the 3m, 5% and 3m, 10%

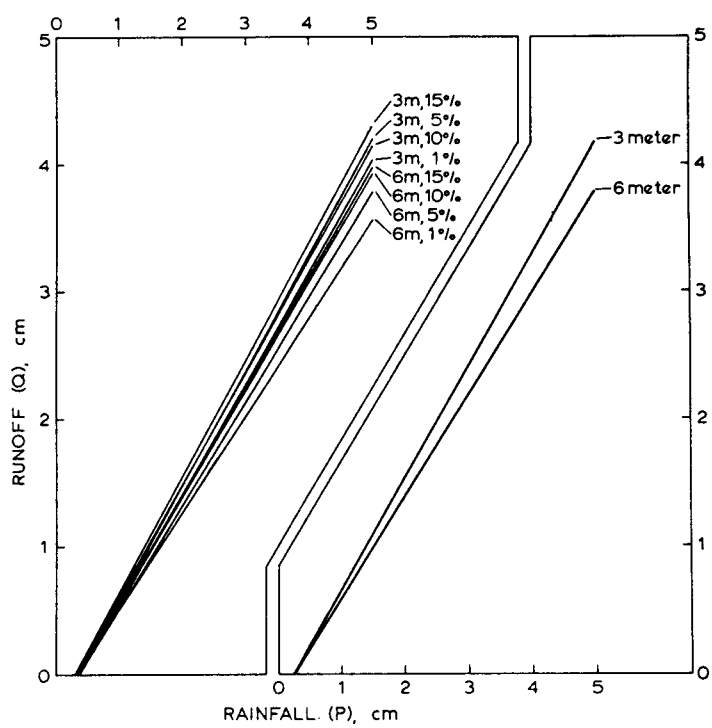

Fig. 1. Linear regression lines of runoff vs. rainfall for each treatment (left-hand side of graph); and, for combined 3-m treatments and combined 6-m treatments (right-hand side of graph).

treatments (Table 1 and Fig. 1). Also, runoff efficiency declines for a given plot slope as the plot length increases from 3 to 6 m. For example, the 3m, 15% treatment had a 19% higher runoff efficiency with $B_1 = 0.92$ than did the 6m, 1% treatment with $B_1 = 0.77$. These differences in runoff efficiency might be explained by the differences in residence time of overland flow on plots having different slopes and lengths.

If rainfall rate, i, is steady and infiltration rate, f, is constant, then the difference $(i - f)$ multiplied by the plot area must equal a constant runoff rate; and, assuming no differences in infiltration rates between plots, then no differences would occur in runoff efficiency between plots. But rainfall is not a steady state process. During the intense convective type rain storms common to the arid southwest, there may be many periods when rainfall intensity is essentially zero. During these periods the amount of infiltration is related to the time required for overland flow to recede from the catchment surface, i.e. the recession time. It is known that the velocity of overland flow is related positively to slope, and it is obvious that for a given velocity the recession time will be greater for longer plot lengths.

Using the kinematic wave approximation to the momentum equation and the laminar flow law;

$$u = (gs/3\nu)h^2 \qquad [4]$$

where u is the average velocity (m/s), g is the acceleration due to gravity, h is the flow depth (m), s is the slope (m/m) and ν is the kinematic viscosity (m^2/s); it can be shown (Rovey, et al., 1977) that the characteristic equations for recession flow over a plane surface after cessation of steady state rainfall are:

$$dh/dt = -f_o \qquad [5]$$

$$dx/dt = g\,(s/\nu)\,h^2 \qquad [6]$$

where f_o is the infiltration rate (m/s). Woolhiser (1984) has derived the recession time, t_a, (s) for a plane surface of downslope length, L_o, (m) under these conditions as:

$$t_a = \left\{\frac{3\nu\, L_o\,(i - f_o)}{gs\, f_o^2\, i}\right\}^{1/3} \qquad [7]$$

where i is the steady-state rainfall rate (m/s).

Under our conditions the infiltration rate quickly drops to near zero (Cluff, et al., 1972). Also, values of the maximum 30 min rainfall intensity, I_{30}, (mm/h) ranged from 2.0 to 16.8 mm/h for our 11 runoff events, which occurred for rainfalls ranging from 4.3 to 30.2 mm. Thus, for our conditions, we would expect that $f_o \ll i$; so that the effect of rainfall intensity in Eq. [7] would become minor. Assuming that infiltration rates are the same for all plots and that $f_o \ll i$, Eq. [7] gives a 59% decrease in recession time as slope is increased from 1 to 15%; and, a 21% decrease in recession time as length is decreased from 6 to 3 m. Recession time would be 68% less for a 3m, 15% plot than for a 6m, 1% plot. These changes in recession time are just the inverse of the trends in our measured changes in runoff ratio and runoff efficiency as slope and length change.

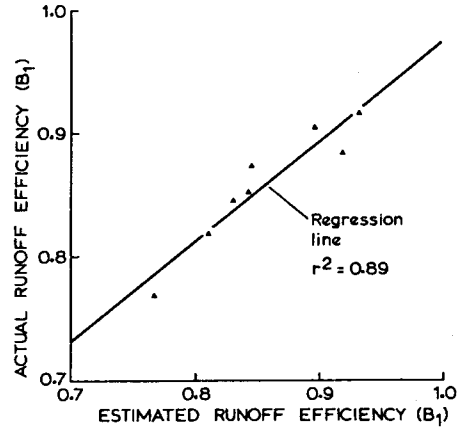

Fig. 2. Actual runoff efficiency, B_1, plotted vs. the runoff efficiency calculated using Eq. [9].

If recession time and runoff efficiency are negatively related then runoff efficiency and thus runoff depth could be some function of slope, downslope length and rainfall intensity (assuming threshold rainfall to be constant). An analysis of variance of runoff depth, Q, with the factors plot slope and downslope length and with the covariates rainfall depth and I_{30} showed that the effects of slope, length and rainfall depth were all significant at the 0.1% level of probability. The effect of I_{30} was not significant even at a 25% level of probability of type I error, so rainfall intensity was not considered in subsequent analyses.

Nonlinear regression (Robinson, 1979) was used to fit several models of runoff depth, Q, (cm) as a function of slope, s, (m/m) downslope length, x, (m) and rainfall depth, P, (cm), the best of which gave:

$$Q = (s^{0.0453}\, x^{-0.183} + 0.183)(P - 0.339) \qquad [8]$$

Equation [8] explains about 99% of the variation in per storm runoff depth. The exponents 0.0453 and −0.183 were significantly different from zero, their approximate 95% confidence intervals being, respectively, 0.0260 to 0.0646 and −0.249 to −0.118. Their signs were as expected from consideration of Eq. [7]. The positive coefficient 0.183 implies that runoff would still occur if the plot slope were zero. The approximate 95% confidence intervals for the coefficients 0.183 and −0.339 were 0.096 to 0.270 and −0.365 to −0.313, respectively.

Note that the coefficient −0.339, equivalent to the threshold rainfall, B_2, in Eq. [1], was very close to −0.340, the value of the threshold rainfall in Eq. [3] which resulted from a linear regression of runoff with rainfall. The runoff efficiency, coefficient B_1 in Eq. [1], can be taken equal to the first term in the right-hand side of Eq. [8] giving:

$$B_1 = s^{0.0453}\, x^{-0.183} + 0.183\,. \qquad [9]$$

Equation [9] explains about 89% of the variability in runoff efficiency as illustrated in Fig. 2. Our experimental results support the theoretical results of Hollick (1974a, b) whose kinematic wave model of catchment runoff predicted runoff depths which indicated increased runoff efficiency as slope increased and as slope length decreased. When Eq. [8] was used to cal-

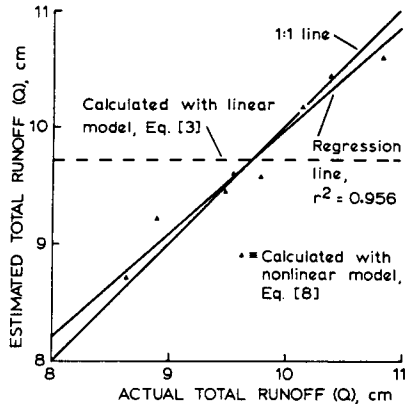

Fig. 3. Total runoff for 18 storms, calculated using Eq. [8], plotted vs. actual average total runoff for each treatment.

culate total runoff for each treatment for the 18 storms it accounted for 96% of the variation in average total runoff per treatment as illustrated in Fig. 3.

Salt Loss and Water Quality

Sodium lost in runoff from the plots paralleled total soluble salt loss and they both showed a fairly strong dependence on plot slope (Table 2). This could be interpreted as an effect on salt loss of either runoff efficiency or erosion rate, both of which increase with slope. Losses of Na calculated as NaCl were between 0.22 and 0.35 Mg ha^{-1} for the 15.1 cm of rainfall. We assume that first year losses of NaCl would range from at least 0.44 to 0.70 Mg ha^{-1} since the average annual rainfall is more than 30 cm and the summer rains are more intense than the predominantly winter rains in this study. However, the losses could have been higher since the runoff from a few rains, occurring before the runoff collection basins were completed, was not monitored.

The revised (Ayers, 1983) FAO classification of irrigation water quality classes waters having an electrolytic conductivity, EC, < 0.75 dS m^{-1} as presenting no salinity problem; waters having an EC of from 0.75 to 3.0 dS m^{-1} are classed as presenting a slight to moderate salinity problem (Ayers and Tanji, 1981). Values of overall EC from Table 2 show that, for all but the 6m, 15% treatment, the runoff would present no salinity problem while for the 6m, 15% treatment there would be a slight salinity problem according to the FAO criteria.

Values of runoff EC for individual events indicate that for some events, such as the 1.73-cm rain of 7 Jan. 1982 (Evett, 1983, p. 133), there would be a slight to moderate salinity problem with the runoff from all treatments. Whether or not those salinity levels would present an actual problem would depend largely on how a microcatchment farming system were designed. The ratio of catchment area to cultivated area, also known as the catchment/cultivated area ratio (CCAR), would be important [see Rands (1980) for a discussion of the CCAR]. An efficient catchment, like the one used in this study, would require a fairly low CCAR to provide for the crop water needs. If the CCAR were of the order of 2:1 to 3:1, then the rain falling directly onto the cultivated area would considerably dilute the runoff water. For most of the EC values we report, such a dilution would reduce salinity to "no problem" levels. Also, if runoff from each treatment were collected in reservoirs for later use in irrigating the crop, the resultant mixing of runoff would eliminate any salinity problem for all but the 6m, 15% treatment as seen from the overall EC values.

Table 2. Averages† of total soluble salt loss (TSS), sodium loss Na and as NaCl, and of overall electrical conductivity (EC) and SAR of runoff for each treatment.

	3 m, 1%	3 m, 5%	3 m, 10%	3 m, 15%	6 m, 1%	6 m, 5%	6 m, 10%	6 m, 15%
TSS (Mg/ha)	0.326	0.429	0.406	0.503	0.391	0.419	0.445	0.556
Na (Mg/ha)	0.088	0.115	0.112	0.136	0.092	0.101	0.111	0.134
NaCl (Mg/ha)	0.223	0.293	0.285	0.347	0.233	0.256	0.283	0.341
EC (dS/m)	0.533	0.660	0.742	0.670	0.708	0.736	0.734	0.888
SAR	4.91	5.40	4.02	6.97	4.18	4.47	4.84	4.95

† Average of two replicates for all but the 6 m, 15% treatment for which data from one replicate were lost due to a leak in a runoff collection basin.

Table 3. Revised FAO irrigation water quality classification for permeability problems.†

	Degree of problem		
	No problem	Slight to moderate	Severe
If SAR = 0 to 3 and EC‡ =	>0.9	0.9 to 0.2	<0.2
If SAR = 3 to 6 and EC‡ =	>1.3	1.3 to 0.25	<0.25
If SAR = 6 to 12 and EC‡ =	>2.0	2.0 to 0.35	<0.35
If SAR = 12 to 20 and EC‡ =	>3.1	3.1 to 0.9	<0.9
If SAR = 20+ and EC‡ =	>5.6	5.6 to 1.8	<1.8

† To evaluate irrigation water quality, first find the range of SAR values that includes the SAR of the water in question; move horizontally to the right in the table and find the range of EC values that includes the EC of the water in question. Finally, move vertically in the table to find if the permeability problem is categorized as "no problem," a "Slight to moderate" problem, or a "severe" problem (Ayers and Tanji, 1981).
‡ EC units are dS/m.

The revised FAO classification of irrigation waters with respect to permeability problems is presented in Table 3. Applying the FAO criteria to the EC and SAR values in Table 2 reveals that for all treatments there would be a slight to moderate permeability problem classification. Permeability problems could actually be increased by dilution of the runoff with rainfall occurring on an adjacent cropped area. This is because dilution decreases EC faster than it does SAR. For example, the runoff from the 3m, 15% treatment on 30 March 1982, had an EC of 0.449 dS/m and a sodium concentration of 72 mg L^{-1}. The SAR is then about 3.8. Under the FAO classification this runoff presents a slight to moderate permeability problem. If the runoff is diluted so that the EC value is reduced by 75% to 0.112 dS m^{-1} and the sodium concentration is reduced to 18 mg L^{-1}, then the SAR value is reduced by only about 50% to about 1.9. For an SAR of 1.9 and an EC of 0.112 dS m^{-1} the FAO classification indicates a severe permeability problem. In actual practice one would not expect this much dilution, and permeability problems would not be expected to increase very much. But, the relationship between dilution of runoff and a consequent increase in permeability problem illustrated above should be kept in mind for design of farming systems using these microcatchments.

Dutt and McCreary (1974, p. 314) reported concen-

trations of total soluble salts and of soluble sodium for earth-tank-held runoff water from compacted earth, NaCl-treated catchments similar to the ones used in this study. Their values were not corrected for dilution by rainwater falling directly into the tank. They reported values of 610 mg L^{-1} total soluble salts and 200 mg L^{-1} soluble sodium declining to about 200 mg L^{-1} total soluble salts and about 50 mg L^{-1} soluble sodium after 2.5 yr. The latter values correspond to an EC of about 0.31 dS m^{-1} and an SAR of about 3.2. These values, like those from this study, indicate a slight to moderate permeability problem according to the FAO criteria. In actual practice permeability and salinity problems have not appeared during the 12 yr that grapes and fruit trees have been grown in water harvesting systems using the same catchment surface treatment on the same soil. (Mielke and Dutt, 1981).

CONCLUSIONS

Although a linear model of the rainfall-runoff relationship accounted for > 97% of the variability in the data, inclusion of plot slope and length in a nonlinear model helped explain important differences among plots in runoff efficiency and total runoff. The nonlinear model (Eq. [8]) accounted for about 96% of the variability in average total runoff per treatment for the 18 storms studied whereas the linear model accounted for no differences in total runoff amongst the treatments. We conclude that a nonlinear rainfall-runoff model incorporating slope and length can account for the important differences in runoff for microcatchments built under our conditions. We did not prove that a relationship exists between recession time and runoff efficiency. But, the fact that runoff depth was not dependent on rainfall rate and the fact that runoff efficiency changed with length and slope, both as expected from consideration of Eq. [7], lead us to believe that this is an important concept which deserves further attention in water harvesting research.

Our water quality studies showed that salinity problems would be minor in water harvesting systems using our catchment. Although a slight to moderate permeability problem was indicated according to the FAO water quality classification, no apparent problems have arisen in 12 yr of use of this type of catchment with grapes and fruit trees on a sandy clay loam of mixed clay mineralogy.

Further studies should address the long-term performance of the sodium dispersed, compacted earth catchment, and should extend the rainfall-runoff relationship for the catchment to soils of different clay mineralogy and texture. Kinematic wave modeling of overland flow should be used to improve our understanding of the physical processes involved and to reduce the number of runoff plots that must be built on each soil.

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