

Susan Bolton holds degrees in organismic biology, zoology, and civil engineering. She received a doctorate in civil engineering from New Mexico State University last summer. Susan has been an engineer with NMSU since 1985 and has worked with Dr. Timothy Ward in the Civil, Agricultural and Geological Engineering Department on several research projects involving rainfall simulation and determining hydrologic properties of southwestern soils.

HYDROLOGIC PROCESSES IN THE PINYON-JUNIPER VEGETATION ZONE OF ARIZONA AND NEW MEXICO

*Susan M. Bolton
and
Timothy J. Ward*

*Department of Civil, Agricultural and Geological Engineering
New Mexico State University
Las Cruces, New Mexico 88003*

*J. Sam Krammes
Forestry Sciences Laboratory
Arizona State University Campus (HFD)
Tempe, Arizona 85787-1304*

INTRODUCTION

The pinyon-juniper (PJ) vegetation type covers much of the semiarid Southwest and at least 17 million hectares of North America (West 1988). It forms the transition zone between the typically overgrazed lower elevation grasslands and the higher elevation pine and fir forests. Pinyon-juniper areas are subjected to a variety of stresses including roads to higher elevations for timber, fuelwood harvest, and livestock grazing. Because the PJ is subject to intense land-use pressures, it is important that land managers have as much information as possible about how the PJ will respond to these pressures.

One important aspect of these pressures is how they affect the movement of water and soil over the land surface. Ideal surface conditions would exist if all incident precipitation would infiltrate and the soil would not erode. In reality, water runs over the soil surface transporting soil particles, litter, and nutrients. This loss of material

reduces potential site productivity and can damage downslope areas through gully erosion or excess loadings of materials to water bodies. To understand the PJ's hydrologic function, controlled experiments must be conducted which measure key variables affecting that function. Specifically, infiltration and erosion parameters which characterize the hydrologic function, and the site variables found in the PJ which influence the parameters, must be identified and quantified. With this information, scientists, managers, and engineers can make informed decisions as to the hydrologic effects of a given land-use practice.

It is a well established conceptual and empirical fact that a bare soil surface erodes more and has a higher volume of runoff than the same soil covered by a canopy, window screen, ground level vegetation, rock, other mulches, or similar types of protection. Gifford (1985) summarized the state of knowledge regarding vegetation effects on runoff and erosion. Among his conclusions and observations were:

- vegetative cover of between 50% to 60% tended to minimize erosion and maximize infiltration; any further increase in cover produced little improvement in either
- there is no consistent evidence to differentiate between the importance of plant species as to their effects on runoff and erosion
- specific infiltration (and erosion) parameters must be decided upon then related to cover to maintain a consistent data base (and provide usable relationships) (parenthetical expressions added by the authors)

Similar discussions of vegetative effects can be found in the multi-paper/chapter publications prepared by Branson et al. (1981), Haan et al. (1982), El-Swaify et al. (1985), Lal (1988), and ASAE (1988), or in most comprehensive hydrology or soil texts.

Beginning in 1985, the U.S. Department of Agriculture began a multiagency research project to develop a hydrologic/hydraulic process-based methodology to complement the often used and much maligned universal soil loss equation (USLE) (Wischmeier and Smith 1978). Gilley et al. (1988) provided a general description of the approaches and methodologies utilized in the USDA sponsored Water Erosion Prediction Project (WEPP). The development phase of WEPP ended in August of 1989 with publication of a manual (Lane and Nearing 1989) and distribution of a microcomputer-based MS DOS program (model). The WEPP has focused the attention of engineers, scientists, and model users on techniques for estimating model parameters and incorporating land management effects in the parameters. Of specific interest are Chapter 4 (Rawls et al. 1989b) on infiltration and Chapter 6 (Alberts et al. 1989) which includes soil erosion. These chapters describe the parameters used in the WEPP model and how they might be modified for cover conditions. Of particular interest are the hydraulic conductivity term in the Green and Ampt (1911) model for infiltration, and the raindrop impact soil detachment coefficient for interrill erosion (e.g., Foster 1982).

The Green and Ampt infiltration equation can be written as:

$$f = K (1 + a/F) \quad (1)$$

where f = infiltration rate (l/T)
 K = hydraulic conductivity (l/T)
 a = the product of wetting front capillary

potential and the difference between antecedent and final (after rainfall stops) volumetric water content (l)
 and F = depth of water infiltrated (l)

The most often sought after and cited parameter in the Green and Ampt equation is the hydraulic conductivity. This is because it is easier to determine from field measurements than is the wetting front capillary potential, and because K , or a function of it, commonly occurs in other infiltration formulae (Rawls and Brakensiek 1985). The hydraulic conductivity, K , can be estimated from a variety of methods based upon soil properties or through data collected from rainfall simulation (e.g., Rawls and Brakensiek 1985; Ward and Bolin 1989a). For rainfall-runoff studies, K is usually presented in units of cm/hr, mm/hr, or in/hr. Typical values of K range from about zero up to about 100 mm/hr, although higher values have been reported. Rawls and Brakensiek (1985), Rawls et al. (1989a), and Rawls et al. (1989b) present techniques for estimating K with correction factors for cover and other effects. Rawls et al. (1989a) reported the results of analyzing data from Hutton (1984) from which they found that:

$$CF = Kc/Knc = (1 + 0.96 Cc) \quad (2)$$

where Kc = hydraulic conductivity under a canopy cover
 Knc = hydraulic conductivity without canopy cover
 and Cc = canopy cover as a fraction

Equation 2 was based on 13 data sets and had a correlation coefficient, r , of about 0.94, or a coefficient of determination, r^2 , of 0.88. In the WEPP manual (Lane and Nearing 1989), the coefficient of 0.96 in Eq. 2 has been changed to 1.0 for both range and agricultural lands. Rawls et al. (1989b) also note that canopy above (vegetative) residue does not appear to have any effect on hydraulic conductivity. Therefore, grass canopy cover should not be used to modify hydraulic conductivity because there is usually residue beneath the grass. In general, hydraulic conductivity should approximately double as canopy cover approaches 100%, based on this analysis.

Density of vegetative and rock cover usually affects plot response to rainfall, but not necessarily as one might expect. This is important because

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many beliefs based upon conventional wisdom can be hypothesized, tested, and confirmed through scientific field tests. Studies of natural rainfall plots in arid regions have found that differences in runoff among plots may be difficult to detect. Cordery et al. (1983) report on runoff from small (25 square meters or about 270 square feet) natural rainfall plots in western New South Wales, Australia. Under some climatic conditions, systematic differences in runoff between plots were not evident despite differences in the plots' physical properties. Runoff from all the plots was lower during a wet period with lush vegetation than during a dry period with sparse vegetation. The authors attributed this difference to the increased interception losses caused by denser vegetation.

Many studies in arid regions that have used rainfall simulators have shown significant differences in plot responses based on vegetative and soil surface conditions. Lane et al. (1987) found rock and gravel cover and canopy cover to be negatively correlated with runoff depth. Kincaid et al. (1964) also found shrub cover, grass and litter cover, and gravel cover to be negatively related to runoff. In contrast, some studies (e.g., Blackburn 1975; Tromble et al. 1974) found rock cover and erosion pavement to be positively related to runoff.

These studies and others that used rainfall simulators in arid and semiarid regions with low vegetative cover have found that cover (shrub canopy cover in particular) is an important factor in reducing runoff and erosion. However, other studies of runoff from natural rainfall plots indicate that differences due to vegetation cover and rock cover are difficult to detect. A rainfall simulator study (Bolin and Ward 1987; Bolton et al. 1990) at the Jornada Long Term Ecological Research (LTER) site north of Las Cruces in south central New Mexico supported the results of the natural rainfall plot studies at the same site regarding sediment yields. In that study, average water and sediment yields were not significantly different between plots with and without shrubs. The natural rainfall data set contained information from low energy storms only. This may help explain why statistical differences were not found between natural rainfall plots with different vegetation and soil characteristics.

At lower energies in a sparsely vegetated area like the Jornada LTER site, the role of rainfall energy predominates in determining runoff and

sediment yield. At higher energy levels, a threshold is reached in terms of additional sediment yield from energy increases alone. It was noted that when simulated rainfall was applied at almost twice the normal rate, some differences appeared which could be attributed to plot cover characteristics. These results are supportive of Gifford's (1985) suggestion that vegetal cover may be of minimal importance in determining infiltration and erosion rates on some semiarid rangelands. He indicates erosion rates may be a complex function of plant-soil-storm characteristics that are not well understood. Gifford also suggests that cover density above about 50% to 60% has little effect on increasing infiltration or reducing erosion. Ward et al. (1990) confirm this observation with data from Ward and Bolin (1989b). It is between the low cover situations like those found at the Jornada and the high cover situations as suggested by Gifford where cover improvements may increase infiltration and reduce soil erosion.

A related measure of surface conditions is "roughness" as measured with a point frame. This type of roughness is defined as the standard deviation of elevation measurements for the plot surface. Jorat (1991) found that point-frame roughness measured parallel to the direction of water flow can be correlated with flow resistance and total cover. This result may explain the findings of Sanchez and Wood (1987) relative to infiltration and sediment yield. The importance of surface roughness was recognized by a WEPP study in which numerous roughness measurements were gathered (Gilley et al. 1987).

Runoff, erosion, and sediment yield are all affected by cover conditions on the soil. The WEPP effort has provided guidance as to how those effects may be quantified for specific parameters related to infiltration and sediment yield. The question remains as to how adequately these quantification schemes can be used to predict runoff and sediment yield from areas not used in WEPP model development. This paper presents results of field-based rainfall simulator studies conducted to assess the hydrologic and hydraulic characteristics of pinyon-juniper (PJ) woodlands. The effects of cover on selected parameters are discussed with regard to the collected data and to the schemes developed in the WEPP effort.

METHODS

Location of Sample Sites

Three sites sampled in this study were located in New Mexico and three were in Arizona (Fig. 1). The sites were, in order of sampling, Beaverhead, New Mexico; Springerville, Arizona; Loco Knolls, Arizona; Heber, Arizona; White Oaks, New Mexico; and San Ysidro, New Mexico. Experiments were conducted in May and June at the Beaverhead, Loco Knolls, Springerville, and Heber sites in 1988 (Ward and Bolin 1989b) on plots with natural vegetation and plots that had all vegetation scraped off. The same rainfall simulator was used at a new Heber site in 1989 to examine the effects of the litter layers beneath trees in the PJ (Ward and Bolton 1991).

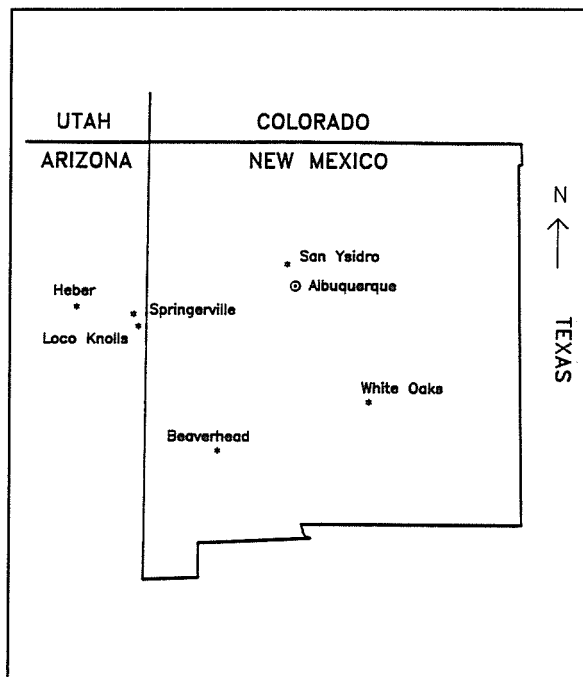


Figure 1. Location of sample sites.

A newly built, modified design, small-area simulator was used at White Oaks and San Ysidro. The experiments were conducted between May 14-15, 1990, at White Oaks and from June 25-28, 1990, at San Ysidro. These experiments, in addition to testing the new rainfall simulator, were designed to determine the effects of burning at White Oaks and the effect of soil type at San Ysidro (Ward and Bolton 1991).

Beaverhead, New Mexico - The Beaverhead site was located north and east of the USDA Forest Service's Beaverhead Work Center in the Gila National Forest west of Truth or Consequences, New Mexico. Eighteen plots were located in Section 36, T9S, R12W, near the junction of forest roads 584 and 953. The site is in a pinyon-juniper area and is adjacent to natural rainfall-runoff plots maintained by M. Karl Wood of the College of Agriculture and Home Economics, New Mexico State University. The simulator plots were located on the flanks of the ridges above the natural rainfall plots. The soils at the site have been described as Lithic Haplustalfs by Charles Souders (personal communication 1988), soil scientist, Gila National Forest, Silver City, New Mexico. Elevation at the site is about 2280 meters. Of the 18 plots, 6 were placed in "high" vegetative cover (based on visual estimates), 6 in "low" cover, and 6 were "scraped" bare (top layer of vegetation and rock removed). Three of the bare plots were protected by a layer of window screen at a height of about 4 inches above the soil surface. The screen was used to create the effect of raindrop impact protection afforded by vegetation and rock cover. Data on 36 plot-runs were collected at this site.

Springerville, Arizona - The Springerville site was located south of Springerville, Arizona, in Section 14, T8N, R29W, on the Apache-Sitgreaves National Forest. Eighteen plots were installed at the site, 6 under the canopy and 12 in the rangeland on the edge of the canopy. The plots were divided into the three groups as used at Beaverhead: high cover, low cover, and bare with and without screen. Site elevation is about 2240 meters. Data on 36 plot-runs were collected during the experiments.

Loco Knolls, Arizona - This site was located east and south of Springerville, Arizona, in Section 6, T8N, R31E. Six plots were located in the rocky rangeland soils on the edge of the canopy. Four of the plots had vegetative cover (two high and two low) and the remaining two were scraped bare. The low cover plots were barely distinguishable from the high cover plots because of the dense vegetation and rock cover at this site. The site is at an elevation of about 2380 meters. Twelve plot-runs were made at this site.

Heber, Arizona 1988 - This site was located within a pinyon-juniper area north and west of Heber,

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Arizona, in Section 33, T13N, R17E. The site is in the Apache-Sitgreaves National Forest at an elevation of about 2000 meters. Twelve plots were sampled; four high cover, four low cover, and four bare (two with screening and two without). Data on 24 plot-runs were collected during the experiments.

Heber, Arizona 1989 - A site near Heber was rained upon in 1988, but in 1989 the experiments were conducted at a new site closer to the large WEPP plots installed by the USDA Forest Service. Fourteen plots were rained upon at the new site in an area north and west of Heber, Arizona, in Section 27, T13N, R17E. The site is in the Apache-Sitgreaves National Forest at an elevation of about 2000 meters. Of the 14 plots, 4 had natural grass cover, 3 were in pinyon-pine litter, 3 were in juniper litter, and 4 plots were scraped bare of vegetation. Data on 28 plot-runs were collected during the experiments.

White Oaks, New Mexico - This site is near the town of White Oaks about 14 miles northeast of Carrizozo. The site is in the Lincoln National Forest, Section 22, T6S, R12E, at an elevation of about 2200 meters. Three plots were placed in areas that had been burned the previous year and three plots were placed in unburned areas. Data on 12 plot-runs were collected at this site. All plots were within the pinyon-juniper canopy.

San Ysidro, New Mexico - This site is about 10 miles south of San Ysidro and 9.4 miles west of the Zia Pueblo near natural rainfall-runoff plots maintained by Earl Aldon of the USDA Forest Service, Albuquerque (Scholl and Aldon 1988). The plots are located within the Jemez River basin at an elevation of about 1850 meters in Section 6, T14N, R1E. The plots are in an open rangeland with scattered PJ vegetation. Four plots were placed in Querencia soils and four plots in San Mateo soils. A total of 16 plot-runs were conducted at this site.

Sample Techniques

Plots were rained upon in an antecedent or "dry" condition and again 6 to 24 hours later in a "wet" condition. Simulations were continued until the runoff rate became steady. Water to be analyzed for suspended sediment concentrations was

collected from barrels of accumulated runoff from each plot. Samples were collected in acid-washed bottles and frozen or kept on ice until analyzed. Runoff water from the experiments was analyzed by the New Mexico State University (NMSU) Soil and Water Testing Laboratory for concentrations of total suspended solids (APHA 1980).

Sediment retained on the surfaces of the collection device, which was not pumped into the collection bucket, was reported as deposited sediment. This material was dried and weighed, then computationally added to the suspended sediment to find total sediment yield. Sediment yields are reported as kg/ha and as kg/ha/mm of runoff. The kg/ha/mm of the runoff term is a concentration term which, if multiplied by 100, gives concentration in mg/l.

Infiltration rate can be computed a number of ways (Ward 1986; Ward and Bolin 1989a; Ward and Bolin 1989b). In this paper, infiltration is computed as the average of the final few (usually three) steady-state loss rates. According to Eq. 1, the steady-state infiltration rate should be equal to the hydraulic conductivity, K . After checking the statistical distributions of the data, infiltration rates and sediment values were log-transformed for analyses.

RESULTS AND ANALYSES

Tables 1 and 2 list the plot characteristics of the experimental plots at each site. Table 1 details the sites visited in 1988. Table 2 details the sites visited in 1989 and 1990.

Rainfall Experiments 1988

Table 3 lists the average steady infiltration rates for the different plot types. Previous analyses (e.g., Ward and Bolin 1989b) indicated that there were significant differences between dry run and wet run infiltration rates with wet run rates being significantly lower. For analyses, low cover plots were those with less than 50% organic cover as measured by the point frame and high cover plots had more than 50% cover.

For the dry runs, the bare-screen and the low cover plots had statistically the same infiltration rates. The high cover plots had significantly higher rates and the bare plots had significantly lower rates than the bare-screen and low cover plots. On

Table 1. Means and standard deviations (in parentheses) of plot characteristics for each site - 1988

Site	#	Cover	Porosity %	Slope %	Canopy Cover %	Organic Cover %	Rock Cover %	Roughness	Amc	
									Dry %	Wet %
BH	3	B	40.9 (2.1)	3.5 (0.7)	* *	* *	* *	*	3.4 (1.7)	25.7 (1.4)
BH	3	BS	43.1 (3.8)	3.3 (1.3)	* *	* *	* *	*	2.1 (0.3)	20.3 (3.5)
BH	6	L	42.0 (4.1)	2.5 (1.0)	9.3 (7.9)	41.1 (15.9)	37.8 (23.5)	0.33 (0.07)	2.5 (0.5)	21.4 (3.8)
BH	6	H	39.3 (4.0)	3.4 (0.5)	19.6 (11.1)	57.6 (12.9)	20.9 (11.5)	0.41 (0.07)	3.2 (1.0)	20.2 (4.1)
HB	2	B	24.0 (16.8)	3.3 (0.4)	* *	* *	* *	*	0.7 (0.1)	15.0 (1.6)
HB	2	BS	47.1 (30.1)	2.3 (0.4)	* *	* *	* *	*	1.8 (1.0)	13.2 (2.6)
HB	4	L	20.6 (6.1)	2.8 (1.0)	18.0 (12.6)	27.7 (22.0)	32.0 (14.1)	0.42 (0.06)	1.0 (0.3)	10.7 (2.6)
HB	4	H	37.2 (21.8)	2.3 (1.0)	12.3 (4.7)	41.3 (28.5)	27.7 (14.5)	0.47 (0.13)	1.4 (0.8)	12.1 (4.1)
LK	1	B	67.3 -	3.0 -	* *	* *	* *	*	4.7 -	30.6 -
LK	1	BS	67.3 -	3.0 -	* *	* *	* *	*	4.7 -	30.6 -
LK	2	L	52.2 (0.8)	3.5 (0.7)	36.7 (14.7)	52.7 (0.9)	14.7 (10.0)	0.51 (0.01)	4.1 (0.1)	31.2 (6.6)
LK	2	H	52.2 (0.8)	3.0 (0.0)	39.3 (2.8)	55.3 (4.7)	21.3 (1.9)	0.57 (0.05)	4.1 (0.1)	31.2 (6.6)
SP	3	B	58.8 (7.1)	4.8 (1.8)	* *	* *	* *	*	3.6 (0.5)	23.4 (3.8)
SP	3	BS	58.8 (7.1)	4.7 (0.6)	* *	* *	* *	*	3.6 (0.5)	23.4 (3.8)
SP	6	L	52.1 (10.4)	5.6 (2.3)	32.2 (11.8)	19.6 (6.5)	25.8 (17.6)	0.35 (0.07)	3.8 (1.3)	20.2 (0.5)
SP	6	H	48.1 (10.2)	4.8 (1.8)	29.6 (24.0)	64.4 (24.0)	6.0 (6.5)	0.36 (0.08)	3.8 (1.3)	19.8 (1.0)

Amc = antecedent soil moisture

BH = Beaverhead; HB = Heber 1988; LK = Loco Knolls;

SP = Springerville; WO = White Oaks; SY = San Ysidro

- number of plots at each location

* - data not collected

Cover - assigned cover categories; B = bare; BS = bare-screened;

L = low cover; H = high cover

Note: Organic cover is basal vegetation, cryptogams and litter.

Rock cover is rock and gravel cover.

Roughness is the mean standard deviation in pin heights across and down the plot.

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Table 2. Means and standard deviations (in parentheses) of plot characteristics for each site - 1989 and 1990

Site	#	Cover	Porosity %	Slope %	Canopy Cover %	Organic Cover %	Rock Cover %	Roughness	Amc	
									Dry %	Wet %
HB	4	B	33.9 (7.7)	4.5 (2.7)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.22 (0.06)	2.0 (0.8)	14.3 (8.1)
HB	2	L	20.8 (8.0)	4.8 (0.4)	25.4 (1.9)	26.6 (3.7)	2.6 (1.9)	0.44 (0.01)	0.6 (0.2)	8.6 (1.1)
HB	2	H	40.6 (0.0)	2.5 (0.0)	39.4 (0.9)	54.7 (17.0)	0.6 (0.9)	0.49 (0.03)	2.6 (0.0)	16.9 (1.1)
HB	3	J	46.2 (11.5)	5.7 (0.6)	0.0 (0.0)	100.0 (0.0)	0.0 (0.0)	0.63 (0.06)	4.3 (2.6)	21.2 (7.9)
HB	3	P	58.5 (2.7)	6.8 (3.2)	1.3 (1.4)	100.0 (0.0)	0.0 (0.0)	0.70 (0.09)	6.4 (2.5)	16.2 (8.1)
WO	3	F	56.5 (12.4)	2.5 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	* *	10.4 (4.2)	20.5 (1.7)
WO	3	N	45.8 (2.7)	2.7 (0.8)	32.0 (10.1)	54.7 (17.4)	0.0 (0.0)	0.38 (0.06)	3.5 (0.1)	16.7 (3.1)
SY	4	Q	34.3 (5.2)	4.8 (0.3)	* *	45.0 (4.1)	* *	* *	1.4 (0.1)	14.0 (1.1)
SK	4	M	44.2 (4.8)	2.4 (0.6)	* *	25.2 (13.0)	* *	* *	1.9 (0.2)	16.9 (2.4)

Amc = antecedent soil moisture

BH = Beaverhead; HB = Heber 1989; WO = White Oaks; SY = San Ysidro

- number of plots at each location

* - data not collected

Cover - assigned cover categories; B = bare; L = low cover;

H = high cover; F = burned plots; N = natural plots; P = pinyon litter;

J = juniper litter; Q = Querencia soils; M = San Mateo soils.

Note: Organic cover is basal vegetation, cryptogams and litter.

Rock cover is rock and gravel cover.

Roughness is the mean standard deviation in pin heights across and down the plot.

Table 3. Average infiltration rates (mm/hr) for the four plot types and two moisture conditions. Standard deviations are in parentheses. Values in a given row followed by different letters are significantly different at $p < 0.05$.

Cover Condition	Bare	Bare- screen	Low	High
Number of Plots	9	9	20	16
Dry Run	23.4a (7.2)	39.1b (17.0)	48.6b (16.8)	63.9c (18.6)
Wet Run	14.5a (7.0)	22.3a (13.8)	25.1a (12.5)	39.7b (17.1)

the wet runs, the high cover plots had significantly higher infiltration rates than the other plots. In general, the bare-screen, low and high cover plots had average infiltration rates of about 1.6, 1.9, and 2.7 times, respectively, the average bare plot rate.

Because the published methods did not predict infiltration rates very well (Ward et al. 1990), stepwise regression was used to identify significant relationships between steady infiltration rate and plot characteristics. Residual analysis indicated the presence of one outlier, which was then deleted. A dummy variable of either -1, 0, or +1, respectively, was used for the three cover conditions of bare, low, and high cover. The screened plots were not

used in the analysis because they represented an abnormal condition. The other significant variables were found to be soil moisture and canopy. Soil textures did not enter the relationship at a significant level which may be caused by the low variability in the soil types among the sites relative to the other characteristics. The canopy factor relationship in Eq. 2 could not be duplicated with this data set. However, an increase in r^2 was found when only shrub canopy, rather than total canopy including grass, was used and when it was corrected for litter beneath the canopy. The best relationship for predicting infiltration rate, f , was:

$$f = 41.2 \exp[0.472(\text{fcov}) - 0.031(\text{sm}) + 0.022(\text{canopy})] \quad (3)$$

where f = steady infiltration rate in mm/hr
 fcov = the dummy variable (-1, 0, or +1)
 sm = soil moisture by weight in percent
 and canopy = shrub canopy with no litter beneath it in percent

Equation 3 results in a correlation coefficient of 0.76 between the measured and predicted infiltration rates.

Three other data sets collected with the same rainfall simulator were used to check the validity of Eq. 3. The Jornada data set is from a creosote desert area. The 1989 simulator data (Ward and Bolton 1991) were collected from the same plots as the 1988 samples (Ward and Bolin 1989b), except that there were no bare plots. The Heber 1989 data set is from a PJ area close to one of the 1988 sites. Figure 2 shows the relationship between measured and predicted values of the infiltration rates for the various data sets. Factor lines of 2 times and 0.5 times have been added to the figure to illustrate the variability in the predictions. For the 68 validation data points, the correlation coefficient between predicted and measured values was $r = 0.51$ ($p < 0.0001$).

Overall, 89% of the predicted infiltration rates for the test plots were within a factor of 2 of the measured rates. At individual sites, 92.3% of the Heber 1989 predicted values, 91.7% of the Jornada values, and 85% of the 1989 simulator values were within a factor of 2 of the measured infiltration rates.

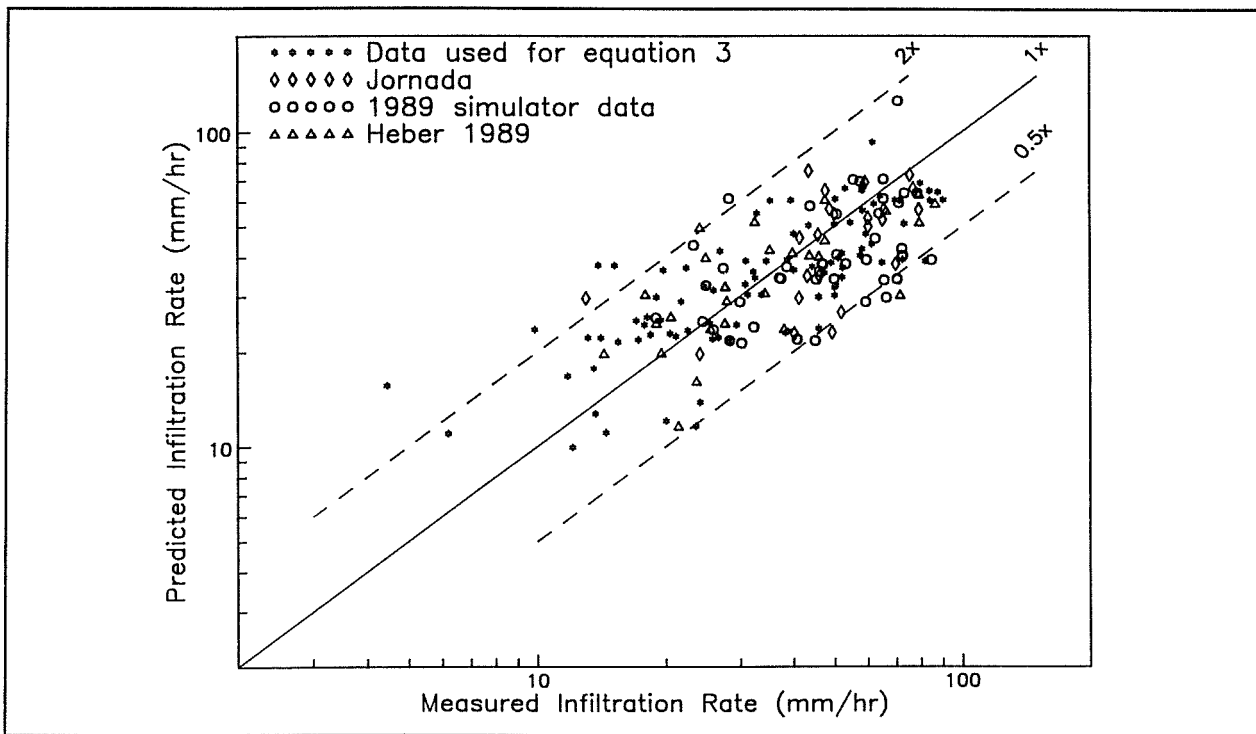


Figure 2. Comparison of measured and predicted infiltration rates.

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Rainfall Experiments 1989 and 1990

Table 4 lists the summarized results of the rainfall experiments at the five sites. Plots at each site were assigned to different cover categories. At Heber there were five plot cover categories: high,

low, pinyon-pine litter, juniper litter, or scraped bare of vegetative cover. At White Oaks, plots either had all vegetation burned off or had natural vegetation. At San Ysidro, plots were not separated by vegetation characteristics, but rather as being situated either in Querencia or San Mateo soils.

Table 4. Means and standard deviations (in parentheses) of rainfall and runoff characteristics for each site.

Site	#	Cover	Intensity (mm/hr)		Runoff/Rainfall (percent)		Steady Infiltration Rate (mm/hr)	
			Dry	Wet	Dry	Wet	Dry	Wet
HB	4	B	88.0 (3.2)	87.9 (2.9)	47.5 (7.1)	69.5 (7.4)	27.6 (7.9)	19.7 (4.0)
HB	2	L	89.0 (3.2)	91.3 (2.8)	32.5 (2.9)	51.4 (4.2)	44.9 (1.6)	31.0 (4.7)
HB	2	H	90.0 (1.9)	90.7 (2.5)	29.6 (3.7)	57.6 (0.5)	43.8 (5.5)	22.8 (3.0)
HB	3	J	87.1 (1.6)	89.4 (2.1)	5.1 (4.5)	36.2 (13.8)	72.9 (9.2)	31.1 (15.0)
HB	3	P	92.2 (2.7)	91.0 (1.4)	22.6 (25.4)	36.8 (17.7)	66.2 (29.3)	43.6 (24.8)
WO	3	F	87.5 (2.8)	90.0 (1.2)	54.9 (20.6)	74.8 (14.4)	34.0 (25.9)	19.7 (15.7)
WO	3	N	91.4 (6.6)	92.7 (2.2)	45.5 (5.3)	64.1 (6.3)	33.3 (4.0)	17.6 (4.4)
SY	4	Q	82.6 (2.3)	83.0 (2.4)	27.6 (4.8)	49.9 (4.5)	48.3 (6.2)	28.7 (1.8)
SY	4	M	83.1 (3.4)	82.8 (4.1)	60.5 (9.8)	79.4 (6.9)	23.0 (8.9)	10.5 (5.6)

HB = Heber; WO = White Oaks; SY = San Ysidro
- number of plots at each location

Cover - assigned cover categories: B = bare; L = low cover; H = high cover;
J = juniper litter; P = pinyon litter; F = burned; N = natural;
Q = Querencia soils; M = San Mateo soils.

Runoff to Rainfall Ratios 1989 and 1990

Comparisons were made at each site among the different cover types. At sites with only two cover levels, t-tests were used and homogeneity of variances were checked. Heber had five levels of cover so a least squares means test was used to test for differences among cover types.

The burned plots at White Oaks had higher mean runoff to rainfall ratios but the differences were not statistically significant for the dry or wet runs. At San Ysidro the San Mateo soils had significantly higher runoff to rainfall ratios than the Querencia soils for dry and wet runs. The Heber dry runs showed considerable overlap in runoff to rainfall ratios among the five cover types. Juniper and pinyon litter plots and the high cover plots had statistically the same runoff to rainfall ratios. The pinyon litter, high and low cover plots were not significantly different and the high, low, and bare plots were not different. At Heber, for the wet runs, the litter plots and the high and low cover plots had statistically the same runoff to rainfall ratios and the low, high and bare plots were not statistically different.

Infiltration Characteristics 1989 and 1990

Small plot data indicate that the estimated average value of hydraulic conductivity (steady-state infiltration or loss rate) decreases between dry and wet runs. Paired difference t-tests were performed on the infiltration rate values between the soil moisture conditions. There were significant differences in infiltration rates at all sites between dry and wet runs.

At Heber, the pinyon-pine and juniper litter plots had significantly higher infiltration rates on the dry runs than the bare plots. There were no significant differences among the other cover categories. For the wet runs, only the pinyon-pine litter plots had significantly higher infiltration rates than the bare plots and there were no statistical differences among the other cover types.

At the other sites, for the dry runs, only San Ysidro had significant differences between plot types. At that site, the differences are not cover related but rather caused by differences in soil

types. For the wet runs, the Querencia soils at San Ysidro again had significantly higher infiltration rates than the San Mateo soils. There were no significant differences in infiltration rates at White Oaks between the burned and unburned plots.

Sediment Production 1988

Tables 5 and 6 report average sediment production for the plots in terms in kg/ha and kg/ha/mm of runoff, respectively. The cover effect is evident in the total yields expressed as kg/ha where the average yields for the bare-screen, low and high cover plots were 0.6, 0.3, 0.2 times, respectively, the average yield for the bare plots. However, when the total yields are expressed in units of kg/ha/mm of runoff, the ratios of the average values for the bare-screen, low and high cover plots are 0.6, 0.5, and 0.6 times, respectively, the average value from the bare plots.

Table 5. Average sediment losses (kg/ha) for the four plot types and two moisture conditions. Standard deviations are in parentheses. Values in a given row followed by different letters are significantly different at $p < 0.05$.

Cover Condition		Bare	Bare-Screen	Low	High
Number of Plots		9	9	20	16
Suspended Sediment Yield	Dry Run	759.1a (483.5)	505.5a (694.2)	134.5b (121.2)	58.4c (62.3)
	Wet Run	447.0a (243.0)	263.5a (175.9)	122.7b (95.3)	104.8b (138.5)

Deposited Sediment Yield	Dry Run	1452.0a (1084.5)	901.9ab (1020.7)	533.1b (348.0)	309.6c (249.8)
	Wet Run	1793.0a (1129.4)	835.1b (614.9)	698.9bc (571.7)	422.1c (259.9)

Total Sediment Yield	Dry Run	2211.1a (1198.7)	1407.4a (1706.8)	667.6b (417.3)	368.0c (290.4)
	Wet Run	2240.0a (1238.6)	1098.6b (611.0)	821.6bc (632.1)	526.9c (352.6)

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Table 6. Average sediment losses (kg/ha/mm of runoff) for the four plot types and two moisture conditions. Standard deviations are in parentheses. Values in a given row followed by different letters are significantly different at $p < 0.05$.

Cover Condition		Bare	Bare-Screen	Low	High
Number of Plots		9	9	20	16
Suspended Sediment Yield	Dry Run	26.5a (14.4)	18.9a (19.1)	8.4b (6.2)	6.5b (4.6)
	Wet Run	18.7a (10.4)	11.4a (5.2)	6.3b (4.5)	5.3b (4.1)
Deposited Sediment Yield	Dry Run	50.9a (33.3)	40.6a (42.5)	39.9a (24.6)	62.6a (57.6)
	Wet Run	76.5a (51.9)	39.2b (30.2)	36.3b (26.2)	25.8b (13.6)
Total Sediment Yield	Dry Run	77.4a (33.4)	59.5a (39.7)	48.3a (27.3)	69.1a (57.5)
	Wet Run	95.2a (57.1)	50.7ab (30.1)	42.7b (28.6)	31.1b (15.8)

Sediment Production 1989 and 1990

Table 7 is a summary of the sediment yields collected with the small simulator in 1989 and 1990. Values were log-transformed for analysis because the log-transformed values were found to be normally distributed and thus met the assumptions of the statistical tests.

At all sites, except Heber, cover conditions were compared with a t-test for differences in total sediment yield from the cover types. Because there are more than two cover types at Heber, a t-test could not be used and a least squares means test was used to test for differences in total sediment yield from the five cover types. Few significant differences were found in total yield between the dry and wet runs, so the analyses were not split by moisture condition.

At Heber, the total sediment concentrations and yields were significantly lower from pinyon-pine and juniper litter plots compared to the other

Table 7. Means and standard deviations (in parentheses) of the components of sediment yield for each site

Site #	Cover	Runoff (mm)		Suspended Yield (kg/ha)		Suspended Conc. (kg/ha/mm)		Deposit (kg/ha)		Deposit (kg/ha/mm)	
		Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet
HB 4	B	88.0 (3.2)	87.9 (2.9)	998.7 (793.8)	939.7 (1172.1)	45.9 (36.0)	35.3 (37.3)	3812.1 (2025.2)	4846.4 (2304.5)	176.0 (95.6)	215.9 (71.9)
HB 2	L	11.2 (0.2)	14.1 (0.5)	89.5 (11.0)	53.9 (2.2)	7.9 (0.8)	3.8 (0.3)	743.7 (142.6)	564.6 (214.8)	66.0 (11.4)	40.3 (16.4)
HB 2	H	13.0 (5.3)	14.8 (1.3)	189.8 (15.0)	212.2 (77.0)	15.7 (5.3)	14.7 (6.6)	928.7 (767.8)	812.6 (395.4)	65.0 (32.7)	54.1 (21.9)
HB 3	J	4.0 (4.5)	18.7 (7.5)	5.8 (6.2)	50.9 (71.1)	3.4 (3.6)	2.5 (3.2)	45.3 (40.3)	358.6 (370.3)	13.7 (16.7)	18.2 (16.2)
HB 3	P	9.9 (11.7)	15.7 (8.2)	48.2 (69.7)	36.3 (30.6)	3.4 (2.0)	2.6 (1.7)	46.5 (25.8)	122.6 (70.7)	9.1 (7.6)	9.8 (6.3)
WO 3	F	20.4 (4.6)	25.0 (4.0)	1168.2 (857.6)	993.3 (406.5)	59.5 (43.4)	39.3 (14.5)	7689.5 (3949.5)	8113.4 (5824.3)	404.7 (274.8)	312.9 (183.2)
WO 3	N	20.6 (10.6)	17.8 (2.1)	534.1 (279.0)	354.9 (34.7)	26.3 (11.5)	20.1 (2.9)	2238.5 (1707.9)	957.0 (683.3)	108.8 (97.1)	54.0 (40.9)
SY 4	Q	13.3 (2.8)	21.7 (2.5)	220.5 (30.0)	319.3 (81.5)	17.2 (4.4)	14.9 (4.2)	2838.8 (2135.6)	2300.5 (1262.2)	210.2 (144.7)	109.5 (64.5)
SY 4	M	21.2 (4.9)	34.6 (8.4)	684.8 (157.5)	1015.4 (443.7)	33.2 (8.4)	28.4 (6.6)	2224.6 (1362.8)	3055.8 (1032.7)	103.2 (56.2)	93.8 (47.9)

Total yields are found by adding suspended and deposit values.

HB = Heber; WO = White Oaks; SY = San Ysidro

- number of plots at each location

Cover - assigned cover categories: B = bare; L = low cover; H = high cover;

J = juniper litter; P = pinyon litter; F = burned; N = natural;

Q = Querencia soils; M = San Mateo soils

cover types. Sediment yields and concentrations were not significantly different from the low and high cover plots. The bare plots had significantly higher total sediment yields and concentrations than the other plots. At White Oaks, the burned-plots had significantly higher total sediment yields and concentrations than the unburned plots. There were no significant differences in sediment yields or concentrations from the two soil types at San Ysidro.

DISCUSSION

The study results reiterate the importance of cover and soil moisture with respect to infiltration rates and erosion. In the stepwise regression for infiltration, the cover variable was the first variable entered for Equation 3 and soil moisture was the second variable entered. An increase in cover increases infiltration rates and decreases soil erodibility. An increase in soil moisture decreases infiltration rates and increases soil erodibility. Soil porosity and soil texture, prominent variables in many models for estimating infiltration parameters, did not enter the stepwise regression as significant ($p < 0.05$) variables. This may be due to the soil similarity among sites in 1988. There were clear differences in hydrologic response at San Ysidro where plots were purposely located in two distinct soil types. Cover was not that different between sites at San Ysidro indicating that soil type can be an influential variable separate from cover. The studies at Heber in 1989 indicate that most runoff and erosion problems in the PJ are from inter-space areas. The litter layers beneath the trees significantly reduce runoff and accompanying soil loss. This effect is probably even more pronounced than indicated by these data since the rainfall simulator rained directly over the litter layer and real rainfall has to penetrate the tree canopy. Earlier analyses (Ward and Bolin 1989b) indicated that soil surface roughness was an important variable for predicting infiltration rate. However, roughness is a difficult variable to estimate quickly in the field and therefore is of limited utility in predictive equations.

Within the limits of comparably measured data, published models for estimating infiltration and erosion parameters were tested with the field data set and found lacking. Equations were developed which better predicted the observed values,

and then were tested on additional data sets. It is important to validate published models, such as those presented here or in the WEPP manual, in order to test their applicability. The results and predictive equations presented in this paper should better help define field conditions which effect runoff and erosion in pinyon-juniper woodlands.

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