A STUDY OF MEASURED VS PREDICTED SOIL LOSS AND STEADY STATE INFILTRATION RATES ON A SEMI-ARID WATERSHED

by

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DEDICATION

I would like to dedicate this thesis in memory of Dale Borgard, I hope that he would have approved.

TABLE OF CONTENTS

TABLE OF CONTENTS (CONT)

LIST OF ILLUSTRATIONS

LIST OF TABLES

A STUDY OF MEASURED VS PREDICTED SOIL LOSS ON A DESERT GRASSLAND WATERSHED

ABSTRACT

Over time, scientists have developed erosion models that predict erosion rates based on certain measurable criteria. The Revised Universal Soil Loss Equation (RUSLE) is a computerized model that uses slope steepness and length, ground cover, the inherent erodibility of the soil, rainfall intensity, and land use practices to predict soil loss on a per hectare basis. This study utilized data collected at the Walnut Gulch Experimental Watershed over a seven-year period to compare the predicted soil loss with actual soil loss. The input parameters for the model were all extracted from existing data collected on the Walnut Gulch Watershed. The predicted soil loss using RUSLE is 72% of the actual soil loss.

INTRODUCTION

Rapid soil loss is of great concern because it causes pollution of surface water supplies and decreases productivity of crop and rangeland (Lake and Shady, 1993 and Colacicco et al., 1989). The ability to accurately estimate soil loss is essential for proper planning of land uses. The most common method of estimating soil loss is by using a model. The Revised Universal Soil Loss Equation (RUSLE) is a model that is designed to be used by an "informed layperson". The skill required by this model is not extensive and a wide variety of people are capable of using this model.

The basic equation of this model is:

$$A = R\ K\ LS\ C\ P$$

Where A is the estimated soil loss (Kg/Hectare) and R, K, LS, C, and P are input parameters for the model. R represents the rainfall energy, which is composed of rainfall intensity and duration. K is the inherent erodibility of the soil and is calculated based on the soil structure, texture, permeability and the amount of organic matter in the soil. LS factor is the slope and length of the site, which indicates the velocity of runoff from the site and the erosivity of the runoff. The C factor is an index of how well the soil is protected from erosion by both an organic and inorganic component. P is a coefficient that represents the conservation practices that are used on the landscape to reduce erosion. In a natural rangeland system the P factor is 1. If a conservation practice is utilized that reduces erosion, then the P factor would be a fraction, representing a decrease in erosion.

This study attempts to measure the ability of RUSLE to accurately predict soil loss in a desert grassland. The study site is located in the Walnut Gulch Experimental Watershed near the town of Tombstone, Arizona. The Walnut Gulch Watershed is operated by the USDA-Agricultural Research Service. The site used in this study is a sub-watershed (112) that is approximately 1.8 hectares in size. This sub-watershed is an active research site where continual rainfall, discharge and sediment loss are measured. By searching the research records for this site, a suitable time frame was found that would allow enough time to determine the long-term erosion rate for this site, as well as provide enough data to support the modeling of the predicted erosion rate. The period is seven years from 1973-1979. In this study, I assume the measured sediment yield to be equal to the erosion rate. This is a reasonable assumption considering the relatively small amount of re-deposition in relationship to the large amount of sediment yield. All soil loss predictions were calculated on a yearly basis, although the data used was measured on a per storm basis. The reason for this is two fold: 1. RUSLE attempts to measure long-term erosion and should not be expected to be accurate on a per storm basis. 2. Past attempts to model erosion on a per storm basis have had limited success (Trieste and Gifford, 1980), primarily because individual erosion episodes are affected by prior rainfall events and existing soil moisture conditions, which can be highly variable.

This research was conducted in cooperation with the USDA-Agricultural Research Service, Tucson, Arizona. Some of the data in this study has been used in previous publications. I have attempted to give credit to the original source of the data when the same data has been in more than one publication.

LITERATURE REVIEW

The Revised Universal Soil Loss Equation (RUSLE) is an update of the Universal Soil Loss Equation (Wischmeier and Smith, 1978). RUSLE has more involved calculations of soil loss, which are facilitated by a computer program (Renard et al, 1996).

The first attempt to mathematically evaluate the factors that affect soil loss were developed by Cook (1936) and consisted of rainfall erosivity, inherent erodibility of the soil, and protection provided by plant cover. Then slope steepness and length were added (Zingg, 1940). Cropping systems and support practices were later added to the equation (Smith, 1941). Smith also developed the idea of soil loss tolerance and presented a graphical representation of soil loss on several midwestern soils. In 1947 soil erodibility and management factors were added to Smith's (1941) equation and additional tables were created to assist in selecting input parameters for the equation (Browning et al, 1947). Smith and Whitt (1948) produced the first equation that was applicable to a large area. It is also the first equation to truly resemble RUSLE. The equation, $A = C\ S\ L\ K\ P$, consisted of a measured soil loss for a claypan soil with a specific crop rotation, slope length, steepness, and row direction. The other factors were dimensionless multipliers used to adjust the C factor for other conditions (Smith and Whit, 1948). Smith and Whitt also addressed the need for a rainfall factor if the model was to be used over several states. The next step in the evolution of erosion models was the development of the Musgrave equation (Musgrave, 1947), which was a model to estimate soil loss in the Corn Belt States. The Musgrave equation contained a factor for rainfall as well as information on how water flow was affected by slope length and steepness, soil characteristics, and vegetation cover. Graphs were prepared that were used to solve the Musgrave equation and these graphs were based on the major soil, climate, and topography conditions in the Northeastern States. A similar project was implemented in Illinois and consisted of nine factors (Van Doren and Bartelli, 1956).

These regional models were so useful that there was a recommendation to develop a national equation. As a result, in 1954 the Agricultural Research Service (ARS) established a National Runoff and Soil Loss Data Center at Purdue University. Their responsibilities consisted of collecting all available data on erosion for further analysis (Wischmeier, 1955). As a result, 10,000 plot-years of data were collected from 48 states to characterize the basic runoff and soil loss characteristics around the United States. In February and July of 1956, a conference was held to address the differences between the existing soil loss equations and to account for areas of the country where no research had been done on soil loss. One of the results of this conference was the establishment of a maximum tolerable soil loss (5 Tons Acre^{-1} year^{-1}). Another outcome was the consensus that there was not enough data available on the characteristics of rainfall throughout the country. Using a combination of the consensus from the conference and the data available from the National Erosion Lab, the Universal Soil Loss Equation (USLE) was developed (Wischmeier and Smith, 1965). The USLE consisted of six factors that represent rainfall, slope length, slop steepness, erosivity of the soil, ground cover, and conservation support practices. The USLE represented a major step in the improvement of soil erosion prediction. This was the first wide scale model that could account for several factors that affect soil loss, and it acknowledged the interrelationships between the factors. The USLE was formally introduced in Agricultural Handbook No. 282 (Wischmeier and Smith, 1965). Later an updated version of USLE was released, Agricultural Handbook No. 537, which accounted for increased knowledge about erosion in general and about erosion of soils in Hawaii (Wischmeier and Smith, 1978). Finally, the RUSLE model was released in 1996 (Renard et al). RUSLE was designed to represent the state of the art technology in erosion prediction and incorporated most of the new literature available on erosion.

MATERIALS AND METHODS

This study was conducted on sub watershed 112 on the Walnut Gulch Experimental Watershed, in Cochise County, Arizona. The vegetation is a transition between Sonoran and Chihuahuan deserts. Sub watershed 112 is 1.8 hectares in size and consists of rolling hills of moderate slope (~10-12%). This site has several favorable characteristics: 1. A similar study was previously conducted on this site using the USLE (Simanton et al, 1980). 2. This is an active research site where rainfall, runoff, sediment yield and cover are measured on a regular basis. 3. This site has been well described with respect to topography and land use history (Simanton et al., 1980).

Rainfall Factor (R)

The USDA, Agricultural Research Service, Tucson AZ, conducts research on the Walnut Gulch Watershed and collects continual rainfall, runoff and sediment yield data in the process. It was therefore possible to utilize existing data sources for most of this project. The rainfall erosivity factor is a measure of the ability of a rainfall event to detach soil particles. The energy of a rainfall event is calculated based on the amount of rainfall for a given interval (Renard et al, 1996).

$$R = \text{Mean (Rainfall energy (E) * Intensity } (I_{30}))$$

The amount of rainfall and the intensity of a storm event were measured using a weighing rain gauge located in the watershed. The cumulative and per storm E_m-values were calculated using equation 2-6 from the RUSLE manual (Renard et al, 1996).

$$E_m = 0.29\,[1 - 0.72\,e^{(-0.05 i_m)}]$$

E_m: Unit Energy of Rainfall (MJ ha^{-1} mm^{-1})

I_m: Rainfall Intensity (mm h^{-1})

Site Location

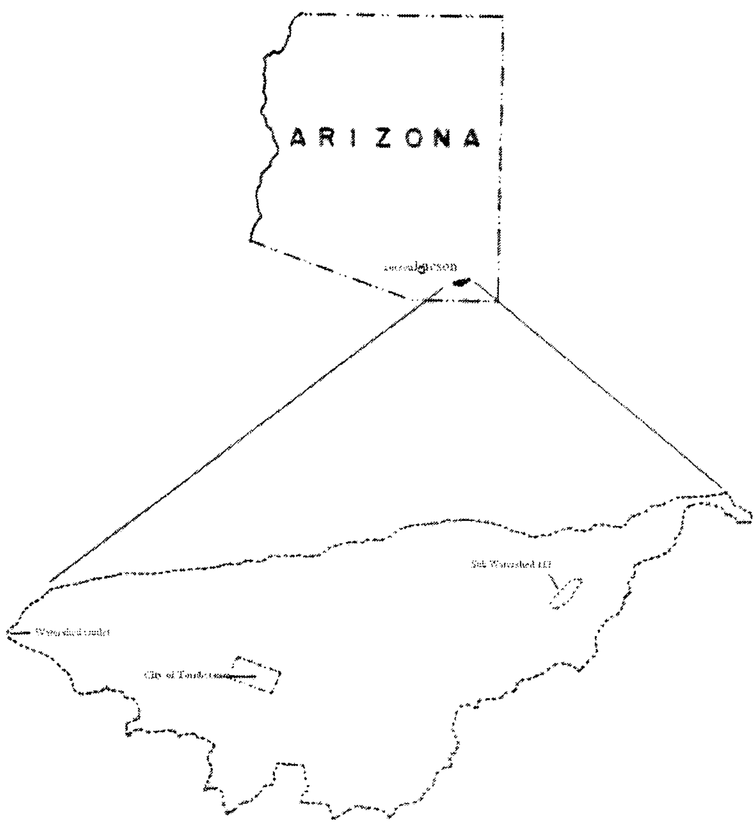

Figure 1. Location of sub watershed 112.

The cumulative R-values were used for this project because past research has had little success with modeling soil erosion on a per storm basis (Trieste, 1980).

Soil Erosivity Factor (K)

The inherent erodibility (K) of the soil is a measurement of the ability of a soil to resist detachment. Several factors are considered when calculating a value for K. These factors are; the fraction of the fine earth fraction that is silt and fine sand, the percent of the fine earth fraction that is sand, the percent organic matter of the soil, the soil permeability, and the soil structure. The K factor can be calculated directly or by using a nomograph (Renard et al, 1996).

$$K = ([2.1 * 10^{-4}(12\text{-}OM)\ M^{1.14} + 3.25(S\text{-}2) + 2.5(P\text{-}3)]/7.59)/100$$

K: $t \bullet ha \bullet h \bullet ha^{-1} \bullet MJ^{-1} \bullet mm^{-1}$

OM: Organic Matter %

M: (0.002-0.1 size fraction %) * (% silt + % sand)

S: Structure class (1-4)

P: Permeability class (1-5)

This watershed consisted of two different soils, Stronghold (Coarse-loamy, mixed, thermic Ustollic Calciorthid) and Elgin (Fine, mixed, thermic Ustollic Paleargid) with approximately 30% Stronghold and 70% Elgin (Breckenfeld, 1993). The soil textural data and the organic matter percent were taken from the Walnut Gulch Soil Survey (Breckenfeld, 1993). The permeability was determined by texture and bulk density (Soil Survey Staff, 1993).

Length Slope Factor (LS)

The length-slope factor is a unit-less scalar that takes into account the effects of length and slope of the topography on the transport of sediments. This factor is a relationship of a relatively uniform slope and the corresponding length of that slope. The slope component is simply the percent slope. The slope length is the horizontal distance of the slope.

The length-slope factor was calculated in the following manner. First, the elevation was determined for every point on a $1m^2$ grid. Then the slopes were grouped together to form polygons. The slope length for each polygon was calculated and the length-slope factor was determined.

Cover Factor (C)

The cover factor accounts for plant material and rock that protect the soil surface from detachment and inhibits transport of sediments by overland flow. The cover factor is calculated by using the following equation (Renard et al, 1996).

$$C = PLU \cdot CC \cdot SC \cdot SR \cdot SM$$

PLU: Prior Land Use

CC: Canopy Cover

SC: Surface Cover

SR: Surface Roughness

SM: Soil Moisture

The data for this calculation were obtained from a vegetation survey that was conducted in 1990-92. Although the vegetation survey is not from the same time frame as the erosion prediction, the data was used for the following reasons. First, there is no vegetation information for this sub watershed for the period of the study. The data correspond well with the RUSLE default values for this type of vegetation community. Finally, it is considered the type of assumption that an actual user of RUSLE might have to make.

Support Practice Factor (P)

The support practice factor (P) is a ratio of the soil loss for a particular soil conservation practice compared to the soil loss without the conservation practice. Rangeland support practices would include any practice that increases infiltration and reduce runoff. Since sub watershed does not have any conservation practices in place, the P value is one by default.

RESULTS AND DISCUSSION

The RUSLE model has five components that are necessary to measure or determine before erosion estimates can be made. Two of these factors are considered constant across the watershed, rainfall erosivity (R) and support practice (P). In this study the rainfall erosivity (R) varies from year to year (Table 1) but the distribution of the R factor across the watershed is considered uniform. As stated previously, the watershed does not incorporate any conservation practices, so the P factor for the entire watershed is one.

Table 1. Yearly erosivity (R) values.

Year	**Erosivity Value (R)**
1973	22
1974	70
1975	48
1976	111
1977	46
1978	26
1979	25

Cover was measured in 1990-92 on the study site (watershed 112) and on an adjacent watershed (111). On watershed 112 vegetation was measured on the north-facing slope. On watershed 111 cover was measured on both the north facing-slope and the south-facing slope as well as for grazed and ungrazed conditions. The vegetation description of watershed 111 was more detailed than the description of watershed 112 so the cover factor was determined by combining the data from both watersheds. The values used for annual site production were from the ungrazed areas because this term represents the potential site production. All other values used to calculate the cover factor came from data on the grazed sections. The vegetation study reveled differences on north and south facing slopes.

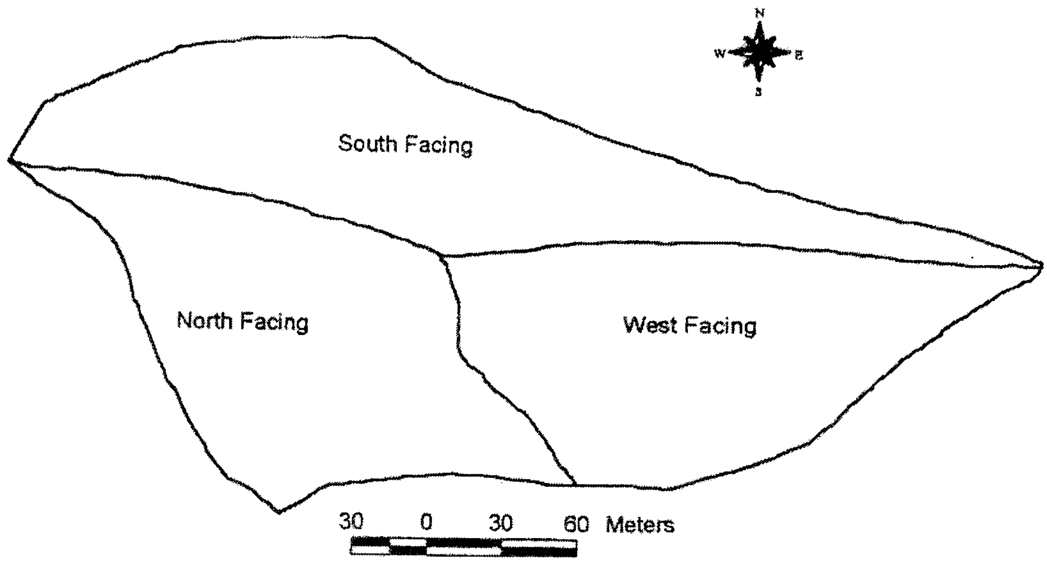

Figure 2. Allocation of cover factor on watershed 112.

Table 2. Data used in calculating cover factor (C) values.

Parameter	North Facing	South Facing
Vegetation Type	Desert Grassland	Desert Grassland
Annual Site Production (lbs/Acre)	1615	2164
Effective Root Mass in top 4" (lbs/Acre)	4361*	5843*
Canopy Cover %	30.2	26.0
Average Fall Height (ft)	.33	.33
Roughness ft/ft	.8	.8
Total Ground Cover % (rock and residue)	54.6	45.4
Surface Cover Function	0.045	0.045
C Factor	0.0007	0.0004

* Value based on estimate calculated by RUSLE

The vegetation study did not look at west facing slopes. Since watershed 112 can be divided into three sections based on aspect, corresponding data was used for the north and south facing slopes and a simple average was used for the west-facing slope (Figure 2). The K factor was calculated using information from the Walnut Gulch Soil Survey (Breckenfeld, 1993) and from estimated permeability using the Soil Survey Handbook (Soil Survey Staff, 1993). The K factors for the Elgin and Stronghold soils are .28 and .10 respectively (Table 3). The Elgin soil occurs on approximately 70% of the watershed and the remaining 30% is Stronghold (Figure 3). The K factor for the Elgin and Stronghold soils were used on the corresponding regions of the watershed for soil loss estimation.

Table 3. Soil characteristics used to calculate inherent soil erodibility factor (K).

Parameter	Elgin	Stronghold
Silt & Very Fine Sand %	32	15
Sand %	26	70
Organic Matter %	1.5	1.5
Soil Structure Class	Blocky (4)	Blocky (4)
Soil Permeability Class	Slow (5)	Moderately Rapid (2)
K Factor	.28	.10

The length-slope factor (LS) was delineated for the watershed by calculating slope for every point on a Digital Elevation Model ($1M^2$ intervals) and clustering these calculated slopes into six regions based on the similarity of slope (Figure 4). A slope length was then calculated for each region. Based on these two inputs an LS value was calculated for each region (Figure 4).

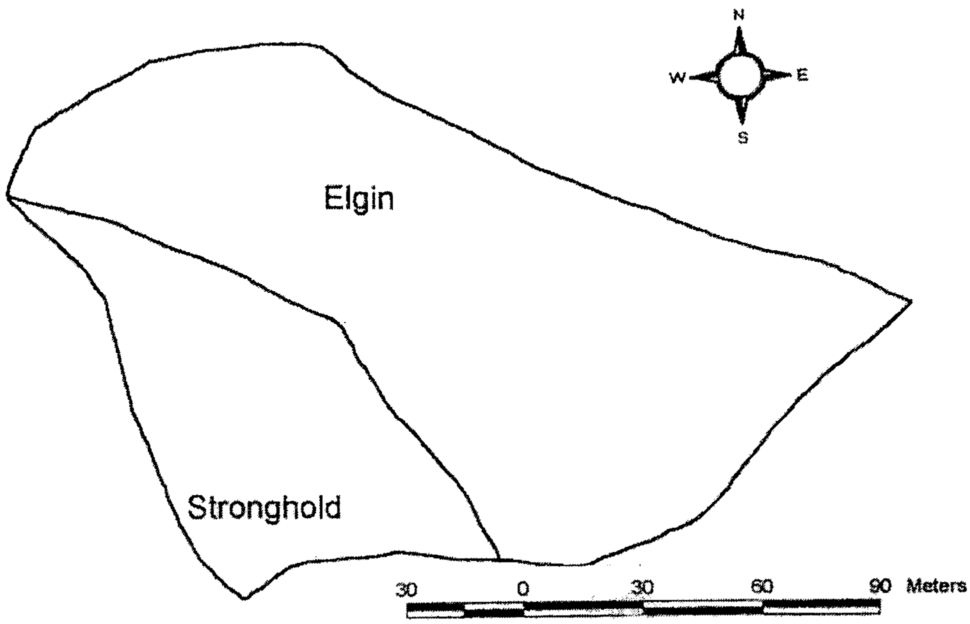

Figure 3. Distribution of soil erodibility factor (K) across watershed 112.

Table 4. Slope percentage, slope length and LS factor for the six sub regions of watershed 112.

Watershed Sub Section	Slope %	Slope Length (ft)	LS Factor
1	11.3	150	1.8
2	21	37.5	2.2
3	10.5	87.5	1.3
4	12	350	2.7
5	12	175	2.1
6	10	287.5	1.9

By combining figures 2, 3, and 4, a composite was made of the intersecting regions. With the addition of the R factor value and P factor (1) soil loss could be calculated using RUSLE for each sub region on the watershed. The summation of these results in the estimated soil loss for sub watershed 112 for that year. Estimated yearly soil loss for the watershed was calculated in this way for the years 1973 though 1979. A plot was then made comparing the cumulative measured sediment yield and the cumulative estimated soil loss (Figure 5).

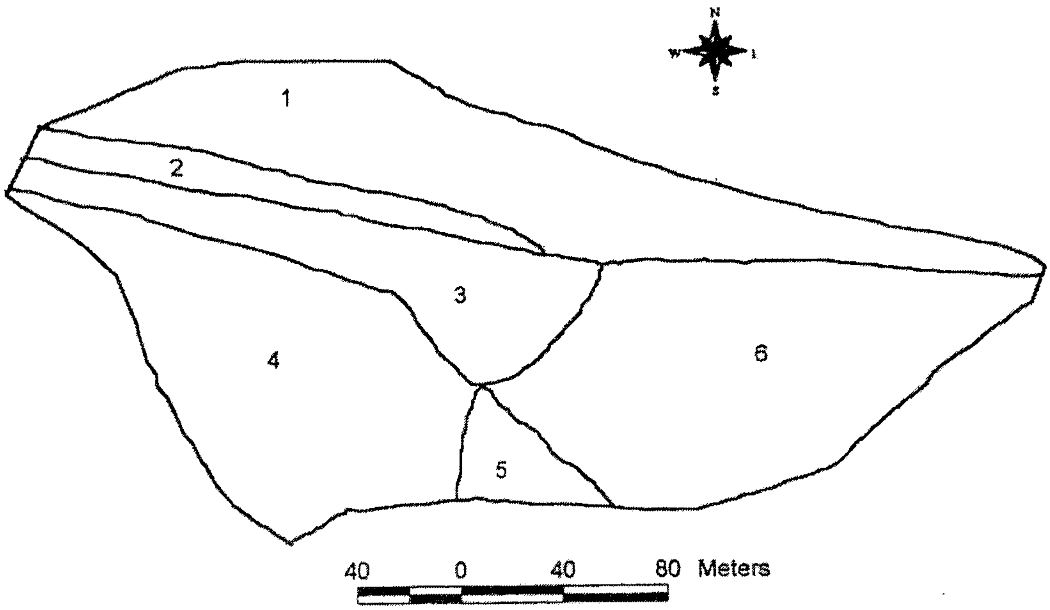

Figure 4. Distribution of slope classes across watershed 112.

The cumulative estimated soil loss seems to model the shape of the actual sediment yield well but under estimates the total amount of sediments removed. To understand this relationship better a plot was made of the cumulative sediment yield and the estimated soil loss (Figure 6). Over all it appears that RUSLE estimate ~72% of the actual sediment yield (Figure 6).

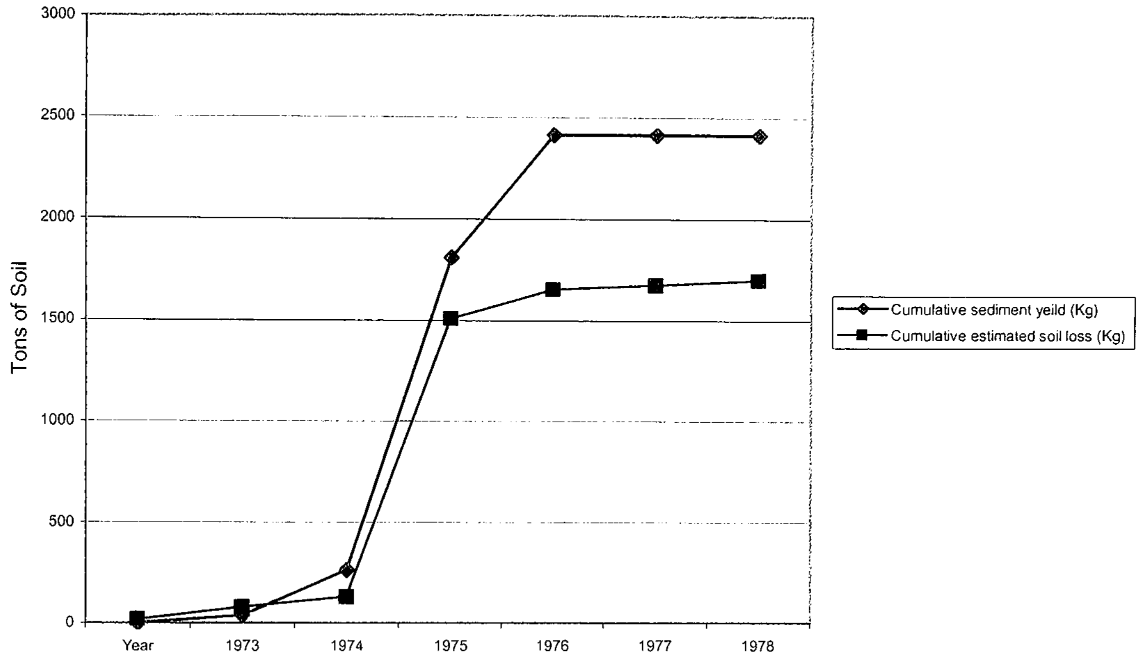

Figure 5. A comparison of measured and estimated cumulative soil loss.

These results are comparable to another study on this same watershed, which compared sediment yield to soil loss estimated by the Universal Soil Loss Equation (Simanton et al, 1980). These results also support other research findings that RUSLE is able to accurately predict soil loss (Bussacca et al, 1993). RUSLE seems to under estimate soil loss in high rainfall years and does an appreciably better job estimating soil loss the remainder of the time.

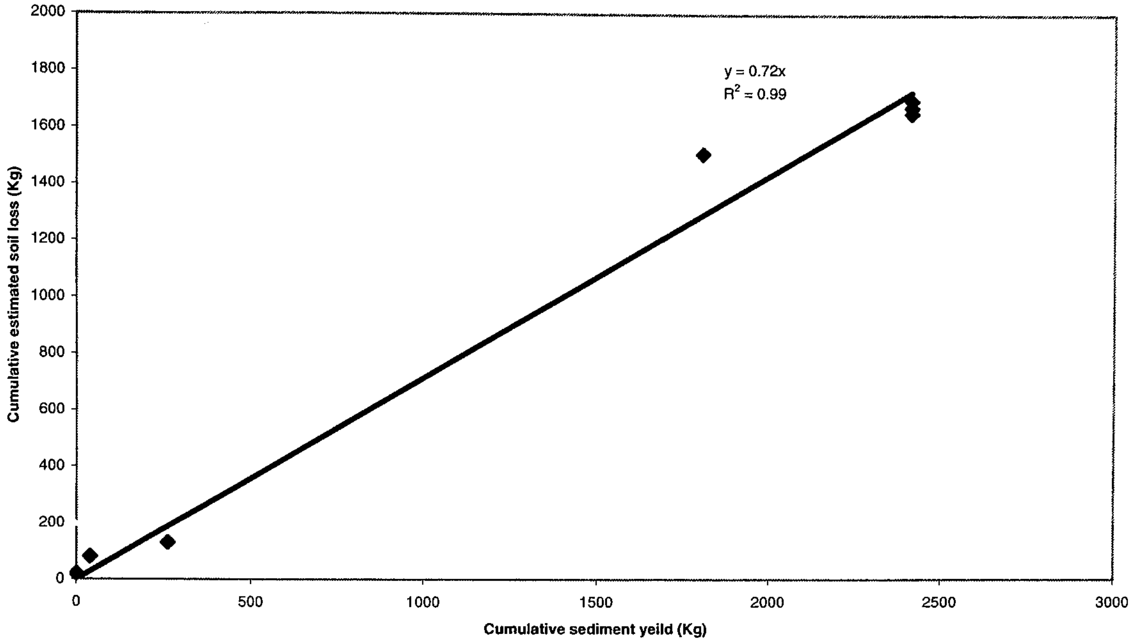

Figure 6. The relationship between measured sediment yields and estimated soil loss.

Conclusions

In this study, RUSLE estimated 72% of the actual soil loss during the period of 1973-1979. In addition, it seems that RUSLE underestimates soil loss during high rainfall years and does a better job during the remaining years. It is unclear why this occurs, but part of the reason might be that the additional runoff transports sediments off site that might otherwise be redeposited on site. There may also be an issue of scaling. That is if we looked at more of the watershed we might find the sediments redeposited some were else. From this study, it seems that RUSLE does a reasonable job estimating the actual soil loss, but more importantly, it consistently tracks the actual soil loss. It would seem reasonable then to scale the results from RUSLE so that they match the actual soil loss.

PREDICTING STEADY STATE INFILTRATION USING COMMONLY COLLECTED FIELD DATA

ABSTRACT

In this study, commonly collected site and soil characteristics were related to steady state infiltration rates. Steady state infiltration rates were measured using a rotating boom rainfall simulator. Stepwise multiple linear regressions were calculated using all of the site data. Additional stepwise multiple linear regressions were calculated for sub sets of the data. These subsets were grouped according to soil series, vegetative treatment and season. From these analyses, I determined that the most important factors in predicting steady state infiltration are canopy cover, ground cover, and season. This study developed several equations to predict steady state infiltration. The best relationships were established when only naturally vegetated sites were used. The equation to predict steady state infiltration under these conditions is:

Infiltration = .55 %Veg. Cover – 15.728 Season + .577 %Litter - .382 % Shrubs + 26.344

INTRODUCTION

The proceedings of the Rainfall Simulator Workshop, January 14-15, 1985 held in Tucson, Arizona include four years of rainfall simulator data collected in spring (April) and fall (October) of 1981-1984 at Walnut Gulch Watershed, Arizona. Four treatments were studied: tilled, bare, clipped, and natural. Data on precipitation, rainfall simulator rates, an erosion index, runoff, sediment eroded, ground cover, and canopy cover are included in the appendices of this publication. This workshop was sponsored by the U.S. Department of Agriculture, U.S. Department of Energy, and the Society for Range Management and the Proceedings were published by the Society for Range Management. Leonard J. Lane, Hydrologist for the USDA Agricultural Research Service, 2000 East Allen Road, Tucson, Arizona 85719 was the editor of the proceedings.

In part 1 of this thesis I discussed the factors in RUSLE used to calculate soil loss per unit area. In this part of my thesis, my interest is in evaluating how soil and land cover characteristics affect the steady state infiltration rates for Walnut Gulch Watershed soils.. Three soils were studied and are identified as being the Bernardino, Hathaway, and Cave soil series. Gelderman (1970) completed a soil survey in 1970, and this is the source of the soils data information. Simanton et al. (1986) include soils data about each soil series and they state that these soils comprise nearly 45% of the Walnut Gulch Watershed. These soils are strikingly different as to their taxonomic classification, yet evaluations of the steady state infiltration rates (or runoff) are similar.

The objective of this research was to return to these plots and collect soil morphology data for each soil. This soil morphology data was combined with plot data recorded in the Proceedings of the Rainfall Simulator Workshop (Simanton et al, 1986) and used to calculate regression equations relating steady state infiltration rate to soil and site characteristics. The data used in this analysis to estimate steady state infiltration can be divided into two broad categories, soil characteristics and site characteristics. Table 6 lists and describes these characteristics. The site characteristics were taken when the rainfall simulator data was collected in 1981-1984. The soil characteristics were measured in the spring of 1997. The difference in timing of the collection of site characteristics and soil characteristics should not affect this study. Soil characteristics that are known to vary over short time periods, such as bulk density and soil structure, were not included in the soil characteristics I studied. Bulk density is difficult to measure in rocky soils and the error of measurement is often very large, and furthermore the bulk densities were likely similar for the three soils. An evaluation of soil aggregation using the wet-sieving method described in Alsharari (1994) for the #50 (0.3mm) and #200 (0.075mm) sieves were measured. This analysis is completed on the <2mm fine earth fraction of the soil, and percentage of soil retained on the sieve is recorded. This is related in some degree to soil structure.

Since the intent of this study is to develop a relationship between steady state infiltration rates and properties that can easily be determined in the field, the data collection techniques are field techniques. This data was supplemented with laboratory data to verify the accuracy of the field measurements. The soil characteristics were determined by five professional soil scientists and the data represents a consensus among the five scientists. This has been shown to be an accurate means of analyzing soil properties (Post et al, 1999). The soil characteristics were determined for both the surface horizon and the horizon that was thought to be the most limiting for water movement. The slopes for all plots ranged from 9.0 to 12.2% and were not included as a variable. The 144 plots can be summarized as follows:

Three Soils (Bernardino, Hathaway, and Cave)
Three Treatments with two replications (Clipped, Bare, and Natural)
4 Years of Data, collected in the spring and fall

Appendix 1 lists all plot data used in this research. Simanton et al (1986) described these treatments as follows: "The clipped treatment consisted of clipping the vegetation at the ground surface, removing the clippings, and controlling any vegetative regrowth with a systemic herbicide. The bare treatment included vegetation clipping and removal, herbicide control, and removing all rock fragments larger than 5mm in diameter from the soil surface that were not partially embedded in the soil. The natural plots were measured as they existed. These initial treatments were made prior to rainfall simulations in the spring of 1981. Retreatments were made before each successive seasonal rainfall simulation".

MATERIALS AND METHODS

This research project was conducted on the USDA-ARS managed Walnut Gulch Experimental Watershed in Southeastern Arizona. Three soil series were studied (Bernardino, Hathaway, and Cave) that represent about 45% of the soil types found on the Walnut Gulch Watershed (Table 5). From 1981 to 1984 Simanton et al (1986)

Table 5. Taxonomic classification of the Bernardino, Hathaway, and Cave soils (Gelderman, 1970).

Soil Series	Taxonomic Classification
Bernardino	Fine, mixed, thermic, Ustollic Haplargid
Hathaway	Loamy-skeletal, mixed, thermic Aridic Calciustoll
Cave	Loamy, mixed, thermic, shallow Typic Paleorthid

conducted rainfall simulation studies on three of the soils during the spring and fall of each year. In these studies, a rotating-boom rainfall simulator was used on two adjacent 3.05m X 10.7m plots. During these experiments precipitation, runoff, ground cover, vegetation cover, and slope were measured. The precipitation and runoff was used to calculate steady state infiltration. Linear regression computations were performed with the soil and site characteristics to better understand the relationship between each characteristic and steady state infiltration. Stepwise multiple linear regressions were preformed using all of the characteristics. In an attempt to gain a better understanding on how soil series, treatment, and season affect steady state infiltration a cascading series of multiple linear regressions was performed were the data set was subdivided by using these parameters so that the variation in predicted steady state infiltration could be analyzed. Once these analyses were performed, a correlation matrix was calculated to determine if the "independent" variables retained in the model were actually independent.

Table 6. Description of the site and soil characteristics that were used to predict steady state infiltration rates.

Characteristic	Description
Treatment	Changes to the vegetation and rock cover on the surface. Natural (no changes), Clipped (all vegetation clipped at the soil surface), Bare (all vegetation clipped at the soil surface and all rock fragments larger than 5mm removed)
Time of year	The season in which the rainfall simulator data were colleted, Fall or Spring
Aggregate stability #50	The percent of soil remaining after gentle agitation on a #50 sieve (Alsharari, 1994)
Aggregate stability #200	The percent of soil remaining after gentle agitation on a #200 sieve (Alsharari, 1994)
% Sand	The estimated percent of sand in the fine earth fraction using the texture by feel methodology (Thien, 1979)
% Clay	The estimated percent of clay in the fine earth fraction using the texture by feel methodology (Thien, 1979)
% Very fine sand	The percent of very fine sand in the fine earth fraction as determined by sieving in the laboratory.
% Very fine sand + %Silt	The sum of the percent very fine sand and the percent silt
% Organic Matter	The percent organic matter in the surface horizon
Stickiness	The stickiness of the soil determined by feel using the soil survey manual guidelines as explained in Post et al (1999)
Plasticity	The plasticity of the soil determined by feel using the soil survey manual guidelines as explained in Post et al (1999)
Dry Color	The dry Munsell color of the fine earth fraction determined by a Minolta CR-200 Chroma meter (Post et al, 1993)
Moist Color	The moist Munsell color of the fine earth fraction determined by a Minolta CR-200 Chroma meter (Post et al, 1993)
% Rock on the Surface	This is the sum of the % rock (>3") and the % gravel (5mm-3") on the soil surface
% Rock in the soil	This is the sum of the % rock (>3") and the % gravel (5mm-3") in the whole soil horizon
%Vegetation cover	The percent of the soil surface covered by vegetation can determined by a pinpoint meter
Detailed Ground Cover and Canopy Cover Data	
Ground Cover	
% Rock on the Surface	The % of rock fragments that are greater than 3 inches in diameter
% Gravel on the surface	The % of rock fragments between 5mm and 3 inches in diameter
% Litter	The % of plant debris covering the surface of the soil
% Bare soil	The % of the soil surface that is not covered by some other form of ground cover
Canopy Cover	
% Grass	The % of the canopy that is grass
% Forbs	The % of the canopy that is forbs
% Shrubs	The % of the canopy that is shrubs

Two sets of variables were used in the multiple linear regression equations. In table 6, all variables are listed and the first 16 variables listed in the table were initially evaluated. Initially, I reasoned that total ground cover and canopy cover were most important and would explain most of the variance, and that while bare soil was important it could be written as 1- other ground cover, therefore it was not necessary to include it. Simanton and Renard (1986) included detailed data on ground cover and canopy cover as: Ground cover includes %Rock, % Gravel, sum of % Rock and Gravel, % Litter, and % Bare soil; Canopy cover includes %Grass, % Forbes, % Shrubs, and % Total canopy cover. I decided to rerun the stepwise multiple linear regression analysis with this additional data includes to see if it could improve the relationships. Therefore, two different data sets were analyzed.

RESULTS

To better understand the variability of steady state infiltration a histogram was made that compared the different soil series and treatments with steady state infiltration rates (Figure 7). There is a general similarity in steady state infiltration between the different soil series when compared to the same treatment. In addition, spring treatments consistently have a higher steady state infiltration rate then corresponding fall treatments.

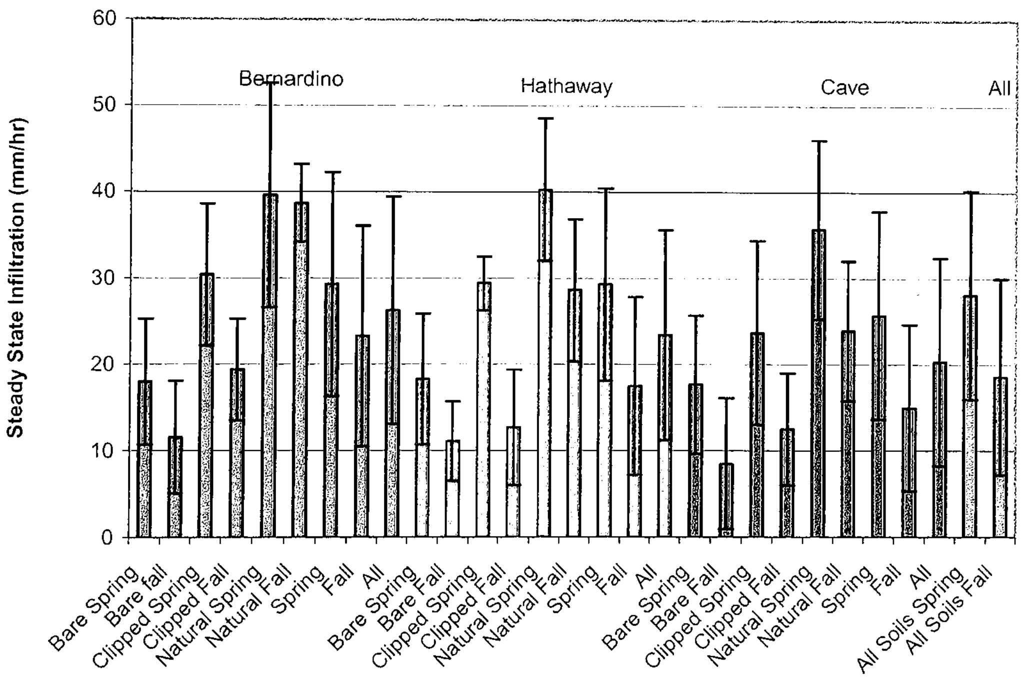

Figure 7. A comparison of steady state infiltration among the different soil-treatment combinations (error bars = 1 standard deviation).

Simple linear regressions were run to compare the relationship between each variable and steady state infiltration. All 144 plots were grouped together and simple linear regressions showed, in general, a very poor correlation between any one characteristic and steady state infiltration (Table 7). The best relationships were with percentage vegetation cover (R^2 = .417) and percentage rock volume in the surface horizon (R^2 = .173).

Stepwise multiple linear regressions were calculated for the entire data set as well as for each cover treatment (Natural, Clipped, and Bare) and by season (Spring and Fall). The results of the stepwise multiple linear regressions using all of the soils are summarized in table 8. The variables are listed in order that they were added to the regression and the corresponding R^2's are listed. The F statistic and corresponding significance represent the entire equation. All of the regressions were highly significant (sig. ≤ .01). The best correlation occurred when only the fall treatments were used (R^2 = .765). When both fall and spring treatments are considered the R^2 drops to .693. While the R^2 for the natural treatment was less than for all of the soils (.627 compared to .693) it was higher than for either the clipped or bare treatments (.518 and .468).

Next, the data set was sub divided by soil series and stepwise linear regressions were performed on each of the combinations of vegetative treatments (Natural, Clipped, and Bare) and seasons (Spring and Fall). These results are shown in Tables 9-11. With the exception of the fall bare plots of the Cave soil series (Table 11) none of the regression equations for the bare or clipped plots are significant (Tables 9-11). They have been included for completeness. The regression equations for the fall treatments generally had higher R^2 values than the corresponding spring treatments.

Table 7. Simple linear regression of each characteristic with steady state infiltration using all plots (N=144).

Variable		All treatments	
		Equation	R^2
Aggregate 50	Surface	Y=-.109x + 27.15	.003
	Sub Surface	Y= .099x + 16.87	.015
Aggregate 200	Surface	Y=. 468x - 17.63	.028
	Sub Surface	Y=.414x - 14.22	.024
% Sand	Surface	Y=.389x - 6.64	.020
	Sub Surface	Y=-.290x + 37.61	.016
% Clay	Surface	Y=-.616x + 28.91	.011
	Sub Surface	Y=.239x + 16.89	.023
% Vf Sand Surface		Y=-1.104x + 35.25	.012
Silt + Vf Sand		Y=-.317x + 31.88	.033
% OM		Y=-3.861x + 28.446	.014
Stickiness	Surface	Y=-18.33x + 37.15	.044
	Sub Surface	Y=2.64x + 16.8	.021
Plasticity	Surface	Y=-6.428x + 28.366	.023
	Sub Surface	Y=3.19x + 14.735	.026
Dry Color Surface	Hue	Y=-7.57x + 53.48	.028
	Value	Y=-5.439x + 46.977	.037
	Chroma	Y=3.733x + 14.37	.019
Dry Color Sub Surface	Hue	Y=-4.759x + 42.958	.036
	Value	Y=-.998x + 27.788	.008
	Chroma	Y=5.423x + 6.953	.036
Moist Color Surface	Hue	Y=-9.290x + 58.291	.033
	Value	Y=-3.735x + 34.194	.004
	Chroma	Y=3.654x + 15.153	.008
% Rock	On Surface	Y=.251x + 12.967	.009
	In Surface	Y=.121x + 18.472	.173
	In Sub Surface	Y=-.002x + 23.502	.001
% Vegetation Cover		Y=.325x + 17.490	.417

Table 8. Summary of stepwise multiple regression models using all soil characteristics and only total ground cover and canopy cover.

Equation Number	Group	Steady State Infiltration mm/hr (s.d.) C.V.%	Equation	R^2	F (sig.)
1	All N=144	23.3 (12.7) 55	Steady state infiltration = .306% Vegetation + .149% Rock on the surface – 12.243Season + 30.705	.429 .634 .693	105.140 (.000)**
2	Natural N=48	34.5 (10.6) 31	Steady state infiltration = .373% Vegetation – 14.640Season + 37.901	.223 .627	37.779 (.000)**
3	Clipped N=48	21.3 (9.9) 46	Steady state infiltration = -12.939Season – 24.553Stickiness of surface horizon + 59.582	.432 .518	24.175 (.000)**
4	Bare N=48	14.2 (7.7) 54	Steady state infiltration = .235% Rock on surface - .234% Rock in surface horizon – 8.577Season + 31.944	.246 .413 .468	12.896 (.000)**
5	Spring N=72	28.1 (12.1) 43	Steady state infiltration = .345 %Veg. Cover + .167 %Rock cover on the surface +17.265	.486 .559	43.665 (.000)**
6	Fall N=72	18.6 (11.4) 61	Steady state infiltration = .278 %Veg. Cover + .128 %Rock cover on the surface - .308 %Sand in the subsurface horizon + 23.376	.690 .746 .765	73.622 (.000)**

Table 9. Summary of multiple linear regressions on subsets of the Bernardino soil using soil characteristics and only the rock and vegetative cover.

Equation Number	Group	Steady State Infiltration mm/hr (s.d.) C.V. %	Equation	R^2	F (Sig.)
7	Bare spring N=8	18.0 (7.3) 41	.01675 Rock cover on the surface– 3.342 Rock cover in the surface + 129.812 OM + 9.552	.439	1.043 (.464)
8	Bare Fall N=8	11.6 (6.5) 56	.237 Rock cover on the surface -.446 Rock cover in the surface + 20.977	.567	3.271 (.124)
9	Clipped Spring N=8	30.4 (8.2) 27	1.44 Rock cover on the surface +22.402 Dry Value in the surface horizon + .751 Rock cover in the surface – 90.939	.352	.723 (.589)
10	Clipped Fall N=8	19.4 (5.9) 30	.04401 Rock cover on the surface – 18.651 Dry Value in the surface horizon -.338 Rock cover in the surface + 101.803	.332	.663 (.617)
11	Nat Spring N=8	39.6 (13.0) 33	.444 %Veg. Cover + 17.204	.700	13.998 (.010)*
12	Nat Fall N=8	38.7 (4.5) 12	.463 %Veg. Cover + 1.785	.823	27.939 (.002)**
13	Spring N=24	29.3 (13.0) 44	.338 %Veg. Cover + 23.629	.520	23.811 (.000)**
14	Fall N=24	23.3 (12.8) 55	.267 %Veg. Cover + .152 %Rock cover on surface +8.966	.773 .854	61.330 (.000)**
15	All N=48	26.3 (13.2) 50	.289 %Veg. Cover + 20.020	.547	55.475 (.000)**

Table 10. Summary of multiple linear regressions on subsets of the Hathaway soil using soil characteristics and only the rock and vegetative cover.

Equation Number	Group	Steady State Infiltration mm/hr (s.d.) C.V. %	Equation	R^2	F (sig.)
16	Bare Spring N=8	18.3 (7.6) 42	.288 Rock cover on the surface - .546 Rock cover in the surface +32.352	.347	1.328 (.345)
17	Bare Fall N=8	11.1 (4.6) 41	.225 Rock cover on the surface + .148 Rock cover in the surface +2.668	.304	1.091 (.404)
18	Clipped Spring N=8	29.4 (3.1) 11	-.000129 Rock cover on the surface – 28.146 OM -.451 Rock cover in the surface + 88.234	.115	.173 (.909)
19	Clipped Fall N=8	12.7 (6.7) 53	-.42 Rock cover on the surface + .28 Dry Value in the surface horizon - .396 Rock cover in the surface + 48.948	.089	.131 (.937)
20	Nat Spring N=8	40.3 (8.3) 21	.361 %Veg. Cover +25.696	.697	13.782 (.010)*
21	Nat Fall N=8	28.6 (8.3) 29	.577 %Veg. Cover – 4.367	.800	23.973 (.003)**
22	Spring N=24	29.3 (11.2) 38	.333 %Veg. Cover + .240 % Rock Cover on surface + 15.252	.613 .805	43.464 (.000)**
23	Fall N=24	17.5 (10.3) 59	.310 %Veg. Cover + 11.562	.731	59.838 (.000)**
24	All N=48	23.4 (12.2) 52	.312 %Veg. Cover + 18.314	.420	33.306 (.000)**

Table 11. Summary of multiple linear regressions on subsets of the Cave soil using soil characteristics and only rock and vegetative cover.

Equation Number	Group	Steady State Infiltration mm/hr (s.d.) C.V. %	Equation	R^2	F (Sig.)
25	Bare Spring N=8	17.7 (8.0) 45	-.02102 Rock cover on the surface - .682 Rock cover in the surface + 48.007	.403	1.685 (.276)
26	Bare Fall N=8	8.5 (7.6) 89	.573 %Rock cover on the surface - .191	.918	67.532 (.001)**
27	Clipped Spring N=8	23.7 (10.7) 45	- .715 Rock cover on the surface - .337 Rock cover in the surface + 70.725	.412	1.752 (.265)
28	Clipped Fall N=8	12.5 (6.5) 52	-.290 Rock cover on the surface - .268 Rock cover in the surface + 39.631	.096	.265 (.777)
29	Nat Spring N=8	35.7 (10.4) 29	79.269 %OM –115.86	.569	7.935 (.030)
30	Nat Fall N=8	23.9 (8.1) 34	137.789 Moist Value in the surface horizon + .478 Rock cover on the surface – 460.768	.728 .883	18.853 (.005)**
31	Spring N=24	25.7 (12.1) 47	.346 %Veg. Cover + 45.179 %OM –63.252	.343 .492	10.179 (.001)**
32	Fall N=24	15.0 (9.7) 65	.285 %Veg. Cover + .186 % Rock Cover on Surface + 4.079	.472 .593	15.304 (.000)**
33	All N=48	20.3 (12.1) 60	.304 % Veg. Cover +36.9 OM – 52.805	.280 .380	13.774 (.000)**

When regression equations were generated for all of the data within one soil series, these equations had lower R^2 values than equations for treatments of season or for the natural vegetation plots. It seems clear from the analysis that canopy cover (%vegetation cover), ground cover (% rock cover on the surface), and season are the three most important factors in predicting steady state infiltration.

Since more detailed canopy cover and ground cover data for these sites were available, as explained earlier, this data was added to my analyses. For this analysis, ground cover was subdivided into % rock cover (rock fragments > 3in), % gravel (rock fragments between 5mm and 3 inches), % bare soil, % litter. These cover totals do not add to 100% because % plant basal area is excluded (The basal area for most plots were less than 2 or 3 %). Since including variables that sum to 100% can be problematic, % plant basal area was not included. Canopy cover was subdivided into % Grasses, % Forbes, and % Shrubs. Four additional stepwise linear regression equations were generated that include this additional data. The four equations are for all of the soils, only spring treatments, only fall treatments, and only natural treatments (Table 12). These stepwise multiple linear regressions have consistently higher R^2 values then the corresponding equations without the detailed surface data (Tables 8 and 12). In this analysis, the most important factors in predicting steady state infiltration are total canopy cover (% vegetation cover), season, and % bare soil.

To assess the accuracy of these models in predicting steady state infiltration a series of plots were made that compare the measured infiltration rates with the predicted infiltration rates (Figures 8-11).

Table 12. Summary of multiple linear regressions with detailed ground and canopy cover data.

Equation Number	Group	Steady State Infiltration mm/hr (s.d.) C.V. %	Equation	R^2	F (Sig.)
34	All N=144	23.3 (12.7) 55	.300 % Veg. Cover – 10.134 Season - .120 % Bare soil + .195 % Litter + 2.210 Plasticity of the subsurface horizon + 32.840	.433 .639 .728 .737 .750	82.581 (.000)
35	Spring N=72	28.1 (12.1) 43	.345 % Veg. Cover - .196 Bare soil + 33.593	.486 .639	61.109 (.000)
36	Fall N=72	18.6 (11.4) 61	.269 % Veg. Cover + .156 % Gravel – 4.487 Value in surface horizon + .332 % Litter + 27.759	.690 .760 .778 .785	65.846 (.000)
37	Natural N=48	34.5 (10.6) 31	.550 % Veg. Cover – 15.728 Season + .577 % Litter - .382 % Shrub + 26.344	.223 .627 .843 .865	68.712 (.000)

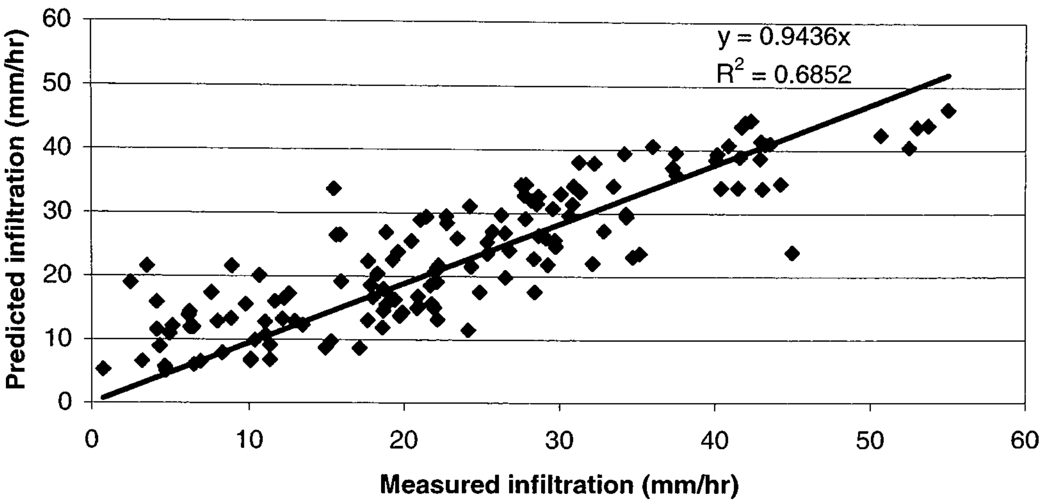

Figure 8. A comparison of measured and predicted steady state infiltration for all soils using detailed ground and canopy cover data (Table 12, equation 34).

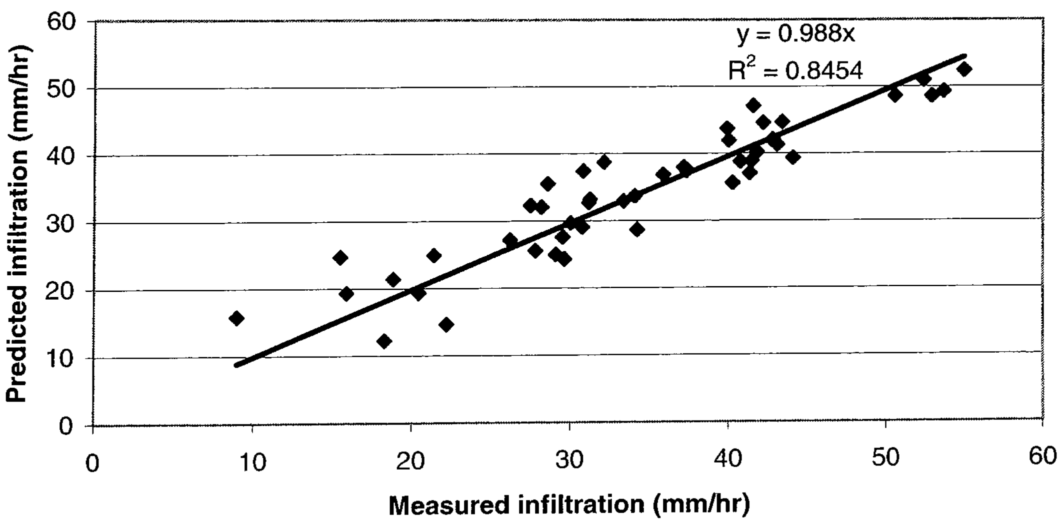

Figure 9. A comparison of measured and predicted steady state infiltration for the natural treatments using detailed ground and canopy cover data (Table 12, equation 37).

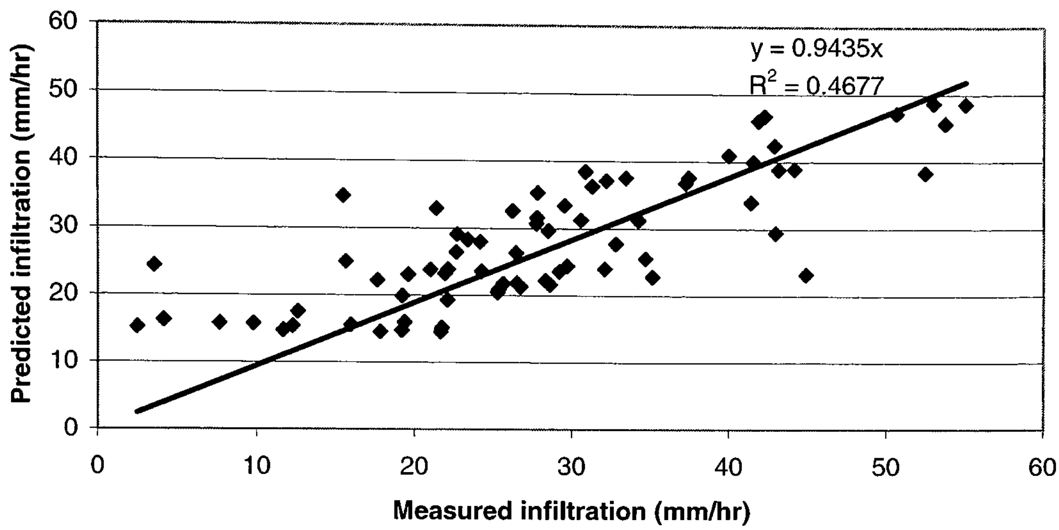

Figure 10. A comparison of measured and predicted steady state infiltration for the Spring treatments using detailed ground and canopy cover data (Table 12, Equation 35).

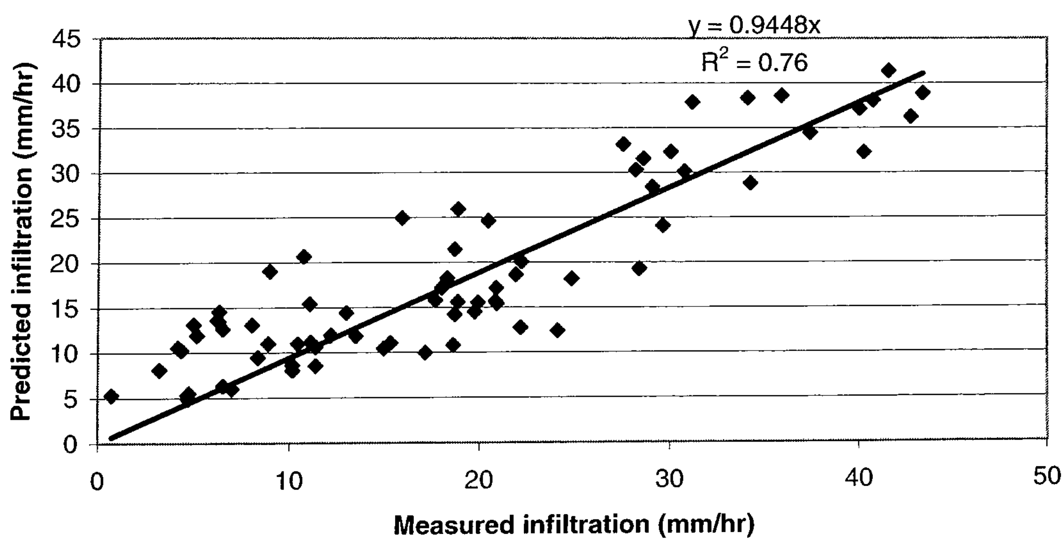

Figure 11. A comparison of measured and predicted steady state infiltration for the Fall treatments using detailed ground and canopy cover data (Table 12, Equation 36).

Out of the four regression equations plotted (Figs. 8-11), the equation for the natural treatment (Table 12, Equation 37) is the most accurate at predicting steady state infiltration. On average, it predicts 99% of the measured infiltration rate and it has a R^2 of .85. The other three Plots (Figs. 8,10, and 11) are all very similar. They all predict ~94% of the measured infiltration rate and there R^2 range from a low of .46 (Fig. 10) to a high of .76 (Fig. 11).

CONCLUSION

In this study it appears that the three aspects of soil-site characteristics that best predict steady state infiltration on these desert rangeland soils are % Vegetation cover, % Litter, and Seasonality. It should be pointed out that although some other models incorporate the use of % bare soil or % rock fragments, instead of % litter, these three variables could be written in terms of one another. This study has developed several practical models for estimating steady state infiltration. The best overall equation for predicting steady state infiltration is under natural vegetative conditions.

$$\textbf{Infiltration} = .55\ \%\ \textbf{Veg. Cover} - 15.728\ \textbf{Season} + .577\ \%\ \textbf{Litter} - .382\ \%\ \textbf{Shrubs} + 26.344$$

It is interesting that the best predictor of infiltration does not have any terms that would be considered soil characteristics.

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APPENDIX 1

Comprehensive Data Table of all Potential Variables used in estimating Steady state infiltration