DISSERTATION

UNIFICATION OF LARGE-SCALE LABORATORY RAINFALL EROSION TESTING

Submitted by

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ABSTRACT

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Water pollution degrades surface waters making them unsafe for drinking, fishing, swimming, and other activities. The movement of sediment and pollutants carried by sediment over land surfaces and into water bodies is of increasing concern with regards to clean waters, pollution control, and environmental protection. Due to increasing environmental concerns about sediment in water bodies derived from construction sites, along with increasingly stringent United States Environmental Protection Agency (USEPA) regulations, it is imperative to be able to have a uniform means to compute soil loss determined at large-scale laboratory rainfall-induced erosion facilities that can eventually be applied to construction sites.

This dissertation utilized bare-soil data from the most commonly-utilized large-scale rainfall testing laboratories in the erosion-control industry to develop a unifying prediction equation that can be utilized to provide a proper foundation for determining design parameters to meet USEPA stabilization requirements. The developed equation was determined to be a function of the following key parameters: rainfall intensity, plot area, duration, slope gradient, median raindrop size, raindrop kinetic energy, percentage of clay in the soil, and compacted soil percentage. The developed equation for the prediction of rainfall-induced soil loss, developed from sixty-eight data points collected for this study, had a coefficient of determination (R^2) of 0.88. The prediction equation unifies large-scale laboratory rainfall erosion testing and provides a means to determine the appropriate design parameters for USEPA stabilization requirements.

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Completion of a dissertation requires patience, sacrifice, and dedication of the student's family. Over the years of schooling and throughout this dissertation, my parents and relatives have been instrumental in providing the necessary love and support for my continued motivation. A big thanks to my wife Darcee, who has provided me with the love and understanding needed to make this goal possible and worthwhile, and to my two children Sarah and Matthew for allowing me to take precious time away from my family to work on my dissertation.

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A	=	plot area (acres)
B	=	regression coefficient, statistical term
C factor	=	cover-management factor
CSL	=	cumulative soil loss (tons/acre)
D	=	duration of the event (hrs)
df	=	degrees-of-freedom
e	=	unit energy
e_r	=	rainfall energy per unit depth of rainfall per unit area (ft-tonf-acre^{-1}-in.$^{-1}$)
E	=	total storm energy
$E(\varepsilon)$	=	mean of the random deviation or random error
EI	=	sum of the computed value for all rain periods within a specified time period
F	=	F-statistic, statistical term
H_0	=	null hypothesis
i_r, *I*	=	rainfall intensity (in./hr)
I_{30}	=	maximum 30-min rainfall intensity
j	=	index of number of years used to produce average
k	=	index of number of storms in each year
k	=	independent variable
K factor	=	soil-erodibility factor
KE	=	raindrop kinetic energy (ft-poundal*1,000)
L factor	=	slope-length factor
LL	=	liquid limit (decimal %)

m	=	mass of raindrop = density of water times volume of sphere with median diameter of the raindrop size of interest
m	=	number of storms in each year
m	=	variable slope-length exponent
MS	=	mean square
MSE	=	mean squared error
MSR	=	mean square due to regression
n	=	number of years used to obtain average *R*
n	=	independent variable
n-*k*-1	=	number of degrees-of-freedom associated with the error sum of squares
% clay	=	percent clay (decimal %)
% compacted	=	surface compaction percentage (decimal %)
% sand	=	percent sand (decimal %)
% silt	=	percent silt (decimal %)
p	=	p-level, statistical term
P factor	=	supporting-practices factor
PI	=	plasticity index (decimal %)
PL	=	plastic limit (decimal %)
R	=	average annual rainfall erosivity
R	=	correlation coefficient, statistical term
R factor	=	rainfall-runoff erosivity factor
R^2	=	coefficient of determination, statistical term
RD_{50}	=	median raindrop diameter (in. and mm)
S	=	slope gradient (decimal %)
S	=	slope gradient of the plot (ft/ft)

S factor	=	slope-steepness factor
SL	=	soil loss (tons/acre and tons/acre/yr)
SS	=	sum of squares
SSE	=	error sum of squares
SSR	=	sum of squares due to regression
SSY	=	total sum of squares
t	=	t-statistic, statistical term
T	=	test duration (hrs)
v	=	velocity of raindrop determined from Laws (1941) velocity raindrop curve
$V(\varepsilon)$	=	variance of the random deviation or random error
$X_1,\ldots..,X_k$	=	predictor variables
X_k	=	k^{th} independent variable
y	=	intercept
Y	=	dependent variable
$\bar{Y}$	=	mean of the dependent variable
Y_i	=	value of a measured data point
α	=	preselected significance level
β	=	ratio of rill erosion caused by flow to interrill erosion
β	=	standardized regression coefficient
β_0	=	y-intercept of the linear relationship
$\beta_0 + \beta_1 X_{1i} + \ldots + \beta_k X_{ki}$	=	equation of the regression line
β_k	=	slope of the regression line for the k^{th} independent variable
Δt_r	=	duration of the increment over which rainfall intensity is considered to be constant (hrs)

ΔV_r	=	depth of rainfall for the r^{th} increment of the storm hyetograph which is divided into m parts, each with essentially constant rainfall intensity (in.)
ε	=	random deviation or random error
Θ	=	slope angle
λ	=	horizontal slope length (ft)
σ^2	=	variance of the regression model

UNITS OF MEASURE

acre(s)-hr-yr	acre(s) per hour per year
decimal %	decimal percent
ft	foot or feet
ft/ft	feet per foot
ft/s	feet per second
ft-poundal*1,000	foot-poundal times 1,000 for convenience
ft-tonf-acre^{-1}-in.$^{-1}$	foot-ton-force per acre-inch
ft-tonf-in.	foot-ton-force-inch
ft^2	square feet
hr(s)	hour(s)
in.	inch(es)
in./hr	inch(es) per hour
in.^{3}	cubic inch(es)
lb(s)	pound(s)
lb(s)/ft^3	pound(s) per cubic foot
lb(s)/in.^{3}	pound(s) per cubic inch
m	meter(s)
m/s	meter(s) per second
min	minute(s)
mm	millimeter(s)
NTUs	nephelometric turbidity units
%	percent
ton(s)/acre	ton(s) per acre
ton(s)/acre/yr	ton(s) per acre per year
yr(s)	year(s)

1 INTRODUCTION

1.1 General Background

Water pollution from sediment degrades surface waters making them unsafe for drinking, fishing, swimming, and other activities. The movement of sediment and pollutants carried by sediment over land surfaces and into water bodies is of increasing concern with regards to clean water, pollution control, and environmental protection. Sedimentation impairs more than 85,000 river and stream miles (United States Environmental Protection Agency (USEPA), 2005). Sources of sedimentation include agriculture, urban runoff, construction, and forestry. Sediment-runoff rates from construction sites, however, are typically 10 to 20 times greater than agricultural lands and 1,000 to 2,000 times greater than forest lands (USEPA, 2005). Figure 1.1 shows an example of construction site erosion and sediment issues. Figure 1.2 shows an example of where the sediment from construction sites often ends up, leading to polluted water bodies.

Environmental concern over construction site erosion is especially evident with continued advancement of rules and regulations originated by the Clean Water Act by the USEPA. As authorized by the Clean Water Act, the National Pollutant Discharge Elimination System (NPDES) permit program controls water pollution by regulating point sources (construction sites) that discharge pollutants into waters of the United States (U. S.).

Stormwater discharges from construction activities (such as clearing, grading, excavating, and stockpiling) that disturb one or more acres, or smaller sites that are part of a larger common plan of development or sale, are regulated under the NPDES stormwater program. Prior to discharging stormwater, construction operators must obtain coverage under an NPDES permit, which is administered by either the State or the USEPA, depending on where the construction site is located.

Figure 1.1 – Example of construction site erosion and sediment issues

Figure 1.2 – Example of sediment pollution into a water body

Where the USEPA is the permitting authority, construction stormwater discharges are almost all permitted under the Construction General Permit (CGP). The newest CGP was published in February 2012 and is in effect until February 2017 (USEPA, 2012) and requires compliance with effluent limits and other permit requirements, such as the development of a Stormwater Pollution Prevention Plan (SWPPP). Construction operators intending to seek coverage under USEPA's CGP must submit a Notice of Intent (NOI), certifying that they have met the permit's eligibility conditions and that they will comply with the permit's effluent limits and other requirements.

Included within the 2012 CGP are a number of modifications, many of which are necessary to implement the new Effluent Limitations Guidelines (ELGs) and new source performance standards for construction and development (C&D) point sources, known as the "C&D rule." C&D rules require construction site operators to meet restrictions on erosion and sediment control, pollution prevention, and stabilization. The C&D rule also includes a numeric turbidity limit of 280 nephelometric turbidity units (NTUs) for certain larger construction sites; but effective January 4, 2011, the USEPA has stayed the numeric limitation of 280 NTUs that was published in the December 1, 2009 rule. The USEPA will propose a revised limit in a future rulemaking.

Within the proposed CGP, there exist new requirements for soil stabilization. According to the new CGP, permitees are required to stabilize exposed portions of a site with erosion- and sediment-control measures such as rolled erosion-control products, hydraulic erosion-control products, and sediment retention fiber rolls. However, the USEPA leaves an important question unanswered, which is how to determine selection of product or type of product for the construction site, but the USEPA does suggest the use of the Revised Universal Soil Loss

Equation (RUSLE; U. S. Department of Agriculture (USDA), 1997) for site analysis and determination of erosion-control products. With the use of the RUSLE equation, the USEPA has connected the construction site to a laboratory test used to determine erosion-control treatment performance, which ultimately has an impact on the amount of soil loss that occurs in the field.

1.2 Research Objectives and Scope

There are hundreds of erosion- and sediment-control treatments specifically designed to protect soil slopes from rainfall-induced erosion on construction sites. One of the most common methods to evaluate performance of erosion-control treatments during rainfall events is to utilize a large-scale rainfall simulation testing facility and then apply the results to construction sites. However, nearly all of the large-scale rainfall testing facilities within the U. S. operate under different rainfall testing protocols which utilize varying slopes, lengths, widths, rainfall amounts and intensities, rainfall drop sizes, drop heights, test duration, soil types, and environmental conditions. Therefore, it is difficult to distinguish or compare treatment performance due to variability in laboratory setups. Further, the cover factor values determined from each laboratory that are then utilized in the RUSLE to meet USEPA soil-stabilization requirements are not comparable from laboratory to laboratory, due to the varied amount of rainfall and time.

Due to the large variability in laboratory setups and the direct link to USEPA-recommended RUSLE usage of the cover factors generated from the laboratories, it is imperative to be able to have a uniform means to compute soil loss determined at large-scale laboratory rainfall-induced erosion facilities that can eventually be applied to construction sites. This dissertation utilized bare-soil data for development of a unifying prediction equation that can be utilized to provide a proper foundation for determining cover factors to meet USEPA and other national and state stabilization requirements across multiple laboratories. Five bare-soil rainfall erosion data sets were obtained from five commonly utilized large-scale laboratory testing facilities. Testing facilities were: 1) ErosionLab® in Wisconsin; 2) San Diego State University in California; 3) Texas Research International/Environmental (TRI) in South Carolina; 4) Texas Transportation Institute (TTI) in Texas; and 5) Utah State University in Utah. The objectives and scope of this research were to:

- Conduct a literature review including a review of: the existing predictive model (RUSLE) and related parameter, and the physical processes that occur during large-scale laboratory rainfall testing to develop the foundation for defining rainfall erosion testing.
- Compile the multiple sets of bare-soil testing data produced from the five testing facilities to provide the foundation for development of a relationship to predict soil loss.
- Identify the most appropriate physical parameters and variables to predict soil loss.
- Perform a statistical analysis and develop a unifying bare-soil loss predictive relationship.
- Compare the predictive relationship to the current standard of practice.

2 LITERATURE REVIEW

2.1 Introduction

Rainfall erosion has been studied for many years and is a very broad topic. The key questions to answer for this literature review are: Why large-scale laboratories are utilized for rainfall simulation and erosion prediction? What are the key rainfall testing? Which erosion models are used to link laboratory data to field implementation that impact construction site design and USEPA requirements? Subsequent sections provide discussion of large-scale laboratory testing, key rainfall testing parameters, and a review of the RUSLE.

2.2 Large-scale Laboratory Rainfall Testing

Rainfall simulators are research tools designed to apply water in a form similar to natural rainstorms (Meyer, 1994). Simulators can be very useful for many types of soil erosion and hydrologic experiments. However, rainstorm characteristics must be simulated properly, runoff/erosion data must be analyzed carefully, and results interpreted judiciously to obtain reliable information for the conditions to which the simulated rainstorms are applied (Meyer, 1994).

One of the major decisions to be determined when setting up a rainfall simulation is to determine how big of an area to be examined. According to Mutchler *et al*. (1994), there are two types of plot sizes reported as: 1) small plots and 2) Universal Soil Loss Equation (USLE) plots (Wischmeier and Smith, 1978). Small plots provide information about infiltration, detachment of particles, and other factors influencing interrill erosion; but small plots do not give complete information about the erosion process. The standard size of small plots is often typified by 18-in. wide by 18-in. long, but can vary. USLE plots are classified as plots that are large enough to represent the combined processes of rill and interrill erosion. The standard size of USLE plots is 72.6-ft long by 13.3-ft wide.

Over the years, many large-scale laboratories began simulating rainfall under controlled conditions to simulate rill and interrill erosion. These laboratories created plot sizes that made sense for their particular setups ranging in length from 20- to 40-ft long and ranging in width from 4- to 8-ft wide. According to Mutchler (1963), all of these size ranges fall within what is classified as sufficient length to develop rill and interrill erosion.

Due to the presence and convenience of many large-scale laboratories, companies, and agencies, organizations began to use the large-scale facilities to examine erosion-control treatments. One particular agency that has suggested the use of large-scale testing facilities to determine erosion performance is the USEPA. The USEPA suggests using the large-scale laboratories to determine a cover factor which then gets applied and used in the RUSLE equation.

During that last 50 yrs, a wide range of equipment and techniques have been utilized to simulate rainfall. These techniques and equipment have ranged from walking up and down the slope with watering cans to elaborate electronically-controlled hydraulic machines (Bubenzer, 1980; Hall, 1970; Meyer, 1958; USDA, 1979). The major methods used to produce simulated raindrops for erosion research can be grouped into three broad categories:

1. *Sprinkler irrigation equipment* that distributes water droplets into the air which fall on the plot. These types of simulators have been found to be less successful in achieving natural rainfall characteristics, especially drop-size distribution and uniformity of application (Lal, 1994). In addition, Holland (1969) concluded that sprinkler heads

positioned 3 m above the plot surface only approximated 50% of the kinetic energy developed by natural rainfall.

2. *Nozzles* from which water is forced at a significant velocity by pressure downward toward the plot. Nozzles produce a wide range of drop sizes, but the large orifices necessary to obtain large drops usually require that the nozzle spray intermittently to reduce application rates to simulate typical rain intensities.

3. *Drop emitters* where drops form and fall from a tip starting at essentially zero velocity. Drop emitters produce a limited range of drop sizes and require higher starting heights to obtain proper impact velocities.

During the last 30 yrs in the erosion-control industry, many rainfall performance tests have been performed. These tests have ranged from simple garden hose and sprinkler setups to full-scale documented field studies. In the middle of the test range are large-scale testing facilities. In the erosion-control industry, there are only a handful of large-scale facilities that are commonly used to regularly evaluate stabilization measures: San Diego State University, Utah State University, Texas Transportation Institute, ErosionLab®, and Texas Research International/Environmental. Figures 2.1 and 2.2 show photographs of typical outdoor and indoor large-scale laboratory setups, respectively.

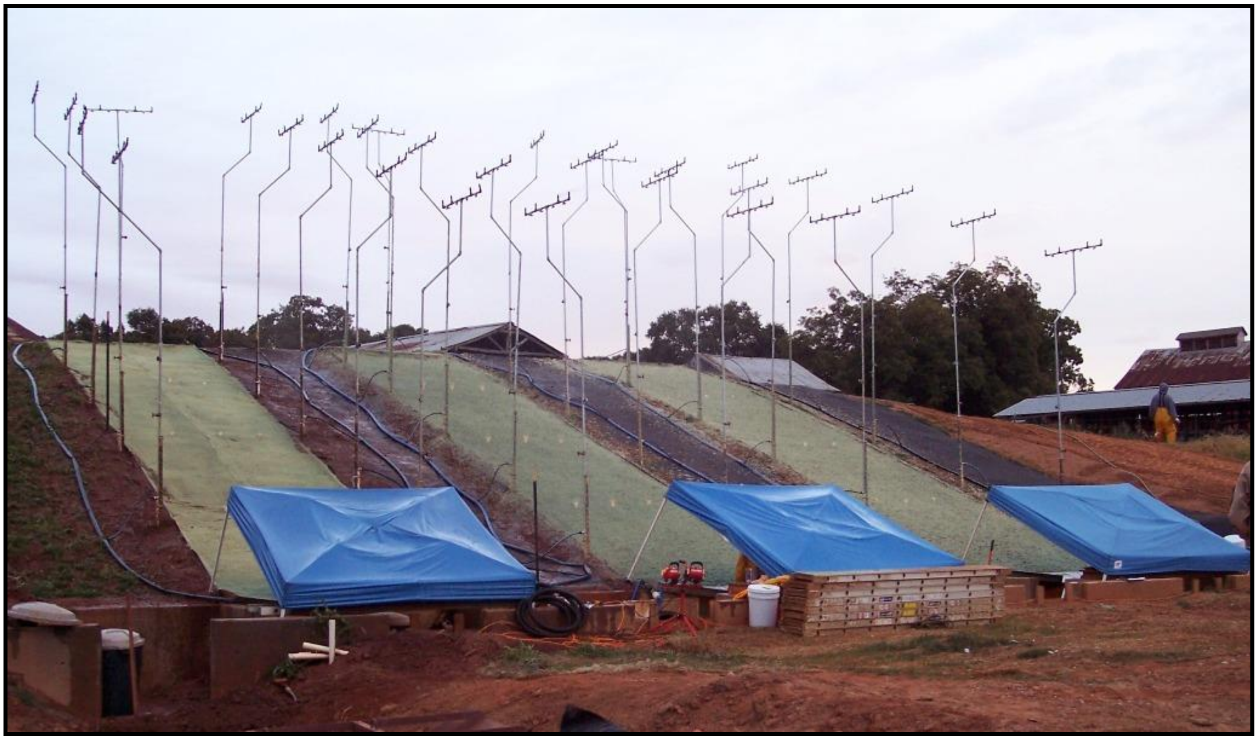

Figure 2.1 – Photograph of typical large-scale outdoor facility

Figure 2.2 – Photograph of typical large-scale indoor facility

2.3 Rainfall Characteristics and Parameters

In order to setup a large-scale testing laboratory, many decisions about setup including slope gradient, plot length, plot width, rainfall quantity and intensity, rainfall drop size, drop height, test duration, soil type, and other environmental and physical conditions need to be determined. According to many researchers, such as Lal (1994) and Meyer (1994), the most important rainfall parameters to be simulated for erosion-control research are: 1) raindrop-size distribution, 2) raindrop-impact velocity, and 3) appropriate rainstorm intensities. These three characteristics can be considered key factors in soil detachment, soil surface sealing, and resulting runoff:

- *Drop-size distribution* near that of natural rainstorms. Natural rainfall consists of a wide distribution of drop sizes that range from near 0 to about 7 mm in diameter. The median diameter is between 2 and 3 mm for erosive rainstorms and increases with rainfall intensity (Laws and Parsons, 1943).
- *Drop-impact velocities* near those of natural raindrops. Raindrop fall velocities vary from near zero for mist-sized drops to more than 29.5 ft/s for the largest sizes. For example, a common-sized raindrop of 2 mm falls at a velocity of 19.7 to 23 ft/s in natural conditions (Gunn and Kinzer, 1949).
- *Intensities in the range of storms* for which results are of interest, which will vary depending on where the erosion is taking place. Intensities of natural rainfall vary from near zero to as high as 15 in./hr. Generally, very low intensities are not of major interest for erosion. Intensities between 1 and 7 in./hr are usually of greatest importance (Lal, 1994).

By examining raindrop size and velocity, many researchers (Lal, Morgan and Nearing, Abd Elbasit, Van Dijk, Laws and Parson, and others) have determined that raindrop kinetic energy can be considered the most significant parameter for predicting rainfall-induced erosion. Kinetic energy of a raindrop is a measure of the amount of mechanical work that each raindrop can perform on the soil. Kinetic energy of a raindrop can be defined as:

$$KE = \frac{1}{2}mv^2 \qquad \textbf{Eq. (2.1)}$$

where

KE = kinetic energy;

m = mass of raindrop = density of water times volume of sphere with median diameter of the raindrop size of interest; and

v = velocity of raindrop determined from Laws (1941) velocity raindrop curve.

Other desirable characteristics for rainfall simulators include (from Lal (1994) and Morgan and Nearing (2011)):

- Based on the fact that raindrop size, velocity, and intensity are critical for rainfall simulation, a widely-used and logical physical parameter for rain simulation is kinetic energy, which represents mass (size surrogate) and velocity. However, kinetic energy does not account for intensity, therefore, a relationship between raindrop size and intensity was developed. A review of the literature to determine the range of natural rainfall data from a large variety of sources and years is presented in Figure 2.3.

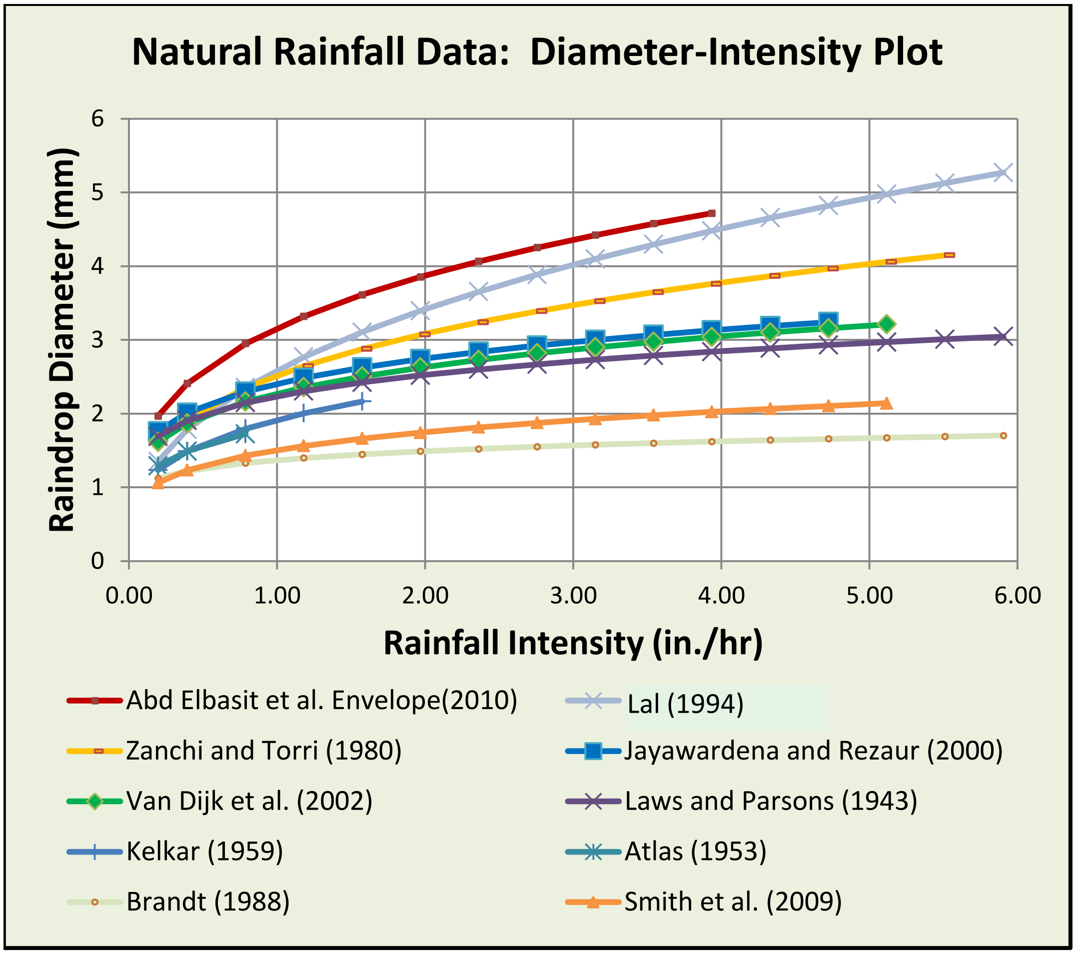

Figure 2.3 – Plot of natural rainfall data: raindrop diameter / rainfall intensity plot

By examining Figure 2.3, it is clear that there is a wide range of raindrop diameters associated with varying rainfall intensity. For example, at 4 in./hr, the reported raindrop size could be anywhere from 1.5 to 4.5 mm. From a conservative design perspective, one could argue that the Abd Elbasit Envelope (Abd Elbasit *et al.*, 2010) should be used for testing of stabliization measures to ensure that the worst-case scenario is represented during testing. However, the more practical and likely more-common raindrop diameter / rainfall intensity relationship that is suggested is that of Van Dijk *et al*. (2002), which represents the average of the possible ranges. Van Dijk's equation is presented for reference as Eq. (2.2):

$$RD_{50} = 2.28 * I^{0.211} \qquad \textbf{Eq. (2.2)}$$

where

RD_{50} = median raindrop diameter (mm); and

I = rainfall intensity (in./hr).

- Plot area of sufficient size to represent the treatment and conditions being evaluated. Rainfall simulators should be capable of applying rainfall to plots that are large enough for a realistic test of treatment characteristics. Square-meter plots and smaller plots may be sufficient for studying raindrop impact (interrill) erosion, but longer plots are necessary for evaluating scour and transport by runoff. Experience has shown that 5 m is the minimum slope length that will adequately represent a rill and interrill erosion system (Lal, 1994; Mutchler, 1963).
- Drop characteristics and intensity of application need to be uniform over the study area.
- Raindrop application needs to be continuous throughout the study area.
- Angle of impact not greatly different from near vertical for most drops.
- Simulators must have the capability of applying the same simulated rainstorm(s) repeatedly.
- Rainstorm conditions must be repeatable when used during common field conditions such as high and low temperatures and winds.

2.3.1 Key Parameters

Based on the information presented in Section 2.3, one arrives at the key function and parameters, which is the ability to simulate rainfall events under controlled and documented conditions and to record the following key parameters shown in Table 2.1 based on input from Lal (1994), Morgan and Nearing (2011), Meyer (1994), and the author's personal research experience.

Table 2.1 – List of key parameters for rainfall simulation (Lal (1994), Morgan and Nearing (2011), Meyer (1994), and the author's personal research experience)

Number	Parameter
1	Soil loss over time
2	Rainfall intensity
3	Plot area (length times width)
4	Duration of test
5	Slope gradient
6	Median raindrop size
7	Raindrop kinetic energy
8	Percentage of sand in the soil
9	Percentage of silt in the soil
10	Percentage of clay in the soil
11	Organic content of the soil
12	Compaction percentage of the finished soil surface
13	Compaction percentage of the underlying soil surface
14	Soil plastic limit
15	Soil plasticity index
16	Soil liquid limit
17	Soil permeability
18	Water runoff volumes over time
19	Turbidity measurements over time

2.4 Rainfall Erosion-prediction Model

Now that we have a better understanding of why large-scale testing facilities are utilized and we also have a good understanding of the key testing parameters, the only question that remains is: How do these data get implemented for use in the field on construction sites? In order to determine the appropriate C factor for USEPA criteria, a rainfall erosion-prediction model is necessary. The USEPA has chosen to support the use of the RUSLE and as such, this dissertation will focus on this erosion-prediction model for development and comparison. In addition, RUSLE is widely accepted as the industry standard for roadway construction sites as the Federal Highway Administration (FHWA) in their *Standard Specifications for Construction of Roads and Bridges on Federal Highway Projects* (FHWA, 2009) requires a design parameter that is only obtained from RUSLE calculations.

2.4.1 RUSLE

In 1954, the USDA developed the USLE (Wischmeier and Smith, 1978) primarily for use on croplands with slopes less than 9%. The USLE was utilized from 1954 until 1987, at which time it was decided that the USLE should be revised to incorporate additional research and technology developed since 1954. The new equation became known as the RUSLE (USDA, 1997), a regression formula which computes the average annual erosion from an acre of land, and computes as follows:

$$SL = R * K * L * S * C * P \qquad \textbf{Eq. (2.3)}$$

where

SL = soil loss (tons/acre/yr);

R = rainfall-runoff erosivity factor;

K = soil-erodibility factor;

L = slope-length factor;

S = slope-steepness factor;

C = cover-management factor; and

P = supporting-practices factor.

The RUSLE was then applied to range lands and forest lands and eventually to construction sites, pushing the use of the equation way beyond the initial intent. For example, of the nineteen key parameters listed in Table 2.1, RUSLE accounts for about eight of the key parameters, namely: soil loss; rainfall intensity; slope gradient; percentages of sand, silt, clay, and organic content; and a yearly time frame. RUSLE is relatively simple to use and implement and, therefore, does have a useful practical value, but also a set of limitations that are often ignored or overlooked (Mathews, 2008). These limitations are:

- the RUSLE only predicts sediment entrained in the erosion process and does not predict sediment yield;
- the RUSLE was intended to predict average annual soil loss and was not intended to be used to predict soil loss for an individual storm event;
- the RUSLE was developed to be effective for erosion by sheet and rill flow on slopes less than 300 m and not for concentrated flow or for longer slopes; and
- the RUSLE does not adequately take into account soil dispersibility when determining the soil-erodibility *K* factor.

2.4.2 *R* Factor

R factor is intended to be a measure of rainfall-runoff erosivity. *R* factor represents the input that drives sheet and rill erosion processes (Renard *et al*., 1994). Differences in *R* factor values represent differences in erosivity. *R* factors can be determined from isoerodent maps, allowing users to interpolate the corresponding *R* factor value for a specific location. The values presented in these maps are produced from decades of observed rainfall data across a given area and are calculated as the product of storm energy times the maximum 30-min storm depth. An isoerodent map of the U. S. is presented in Figure 2.4 for reference, noting that the *R* factor values for the U. S. range from 7 to greater than 800.

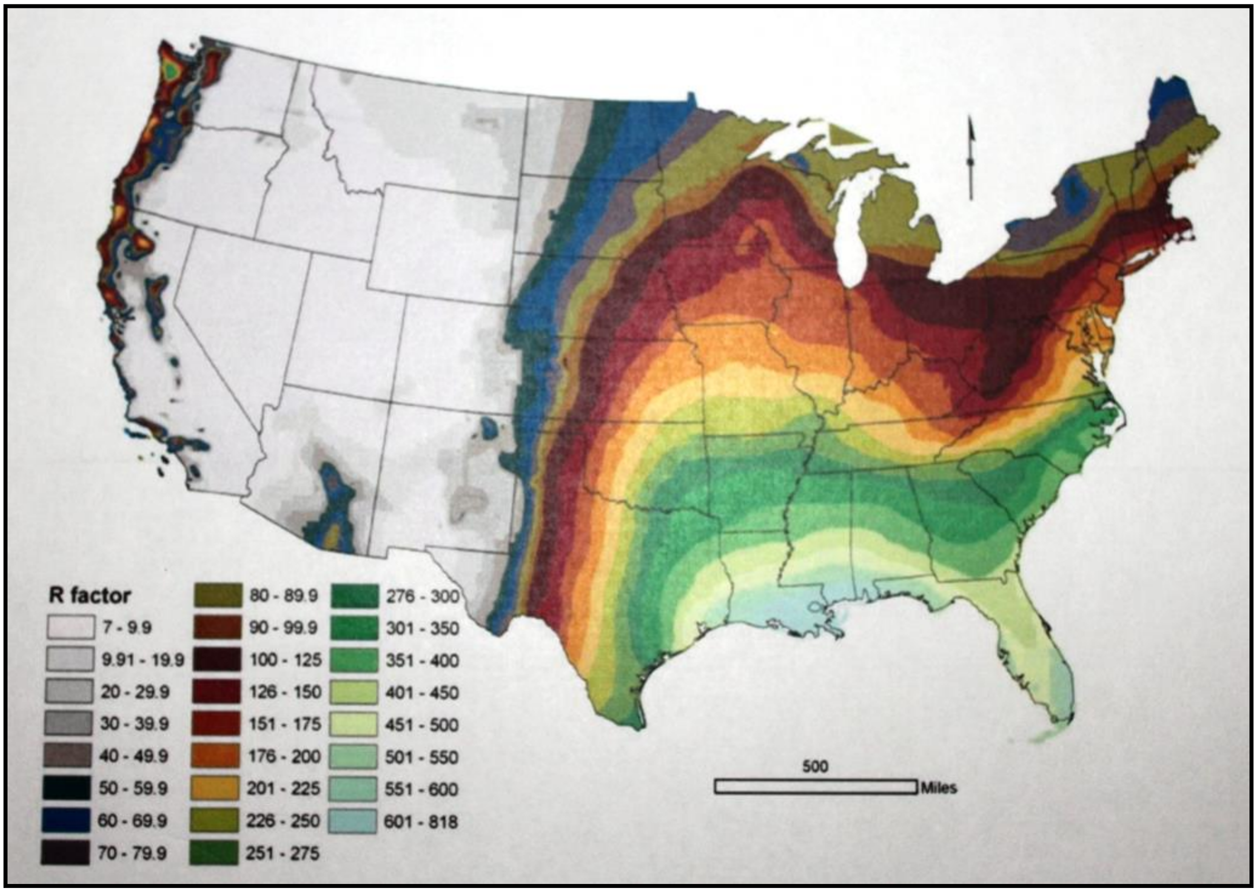

Figure 2.4 – Isoerodent map of the U. S. showing the range of *R* factor values

In addition to the isoerodent maps, *R* factors can be determined from an equation. The following equations obtained from *Agriculture Handbook Number 703* (USDA, 1997) are typically utilized to compute *R* factors for large-scale laboratory testing:

$$R\ \text{factor} = \frac{1}{n}\sum_{j=1}^{n}\left[\sum_{k=1}^{m}(E)(I_{30})_k\right] \qquad \textbf{Eq. (2.4)}$$

where

R factor	=	average annual rainfall erosivity;
n	=	number of years used to obtain average *R*;
j	=	index of number of years used to produce average;
m	=	number of storms in each year;
k	=	index of number of storms in each year;
E	=	total storm energy; and
I_{30}	=	maximum 30-min rainfall intensity.

$$EI = EI_{30} = \left(\sum_{k=1}^{m} e_r \Delta V_r \right) I_{30} \qquad \textbf{Eq. (2.5)}$$

where

e_r = rainfall energy per unit depth of rainfall per unit area (ft-tonf-acre^{-1}-in.$^{-1}$);

ΔV_r = depth of rainfall for the r^{th} increment of the storm hyetograph which is divided into m parts, each with essentially constant rainfall intensity (in.); and

all other variables are defined previously.

Unit energy (e) is a function of rainfall intensity and is computed as:

$$e_r = 1099\left[1 - 0.72 \exp\left(-1.27 i_r\right)\right] \qquad \textbf{Eq. (2.6)}$$

and

$$i_r = \frac{\Delta V_r}{\Delta t_r} \qquad \textbf{Eq. (2.7)}$$

where

i_r = rainfall intensity (in./hr);

Δt_r = duration of the increment over which rainfall intensity is considered to be constant (hrs); and

the other variable was defined previously.

The *EI* for a specified time period (such as the annual value) is the sum of the computed value for all rain periods within that time. Thus,

$$R = \sum EI_{30}\left(10^{-2}\right) \qquad \textbf{Eq. (2.8)}$$

where

R = average annual rainfall erosivity in $\frac{\text{hundreds of ft-tonf-in.}}{\text{acre-hr-yr}}$.

The division by 100 is made for the convenience of expressing the units.

2.4.3 *K* Factor

K factor is the soil-erodibility value and can be defined as the rate of soil loss per rainfall erosion index unit as measured on a unit RUSLE plot. In practical terms, the *K* factor is the average long-term soil and soil profile response to the erosive powers of rainstorms (USDA, 1997). *K* factor represents an integrated average annual value of the total soil and soil profile reaction to a large number of erosion and hydrologic processes, consisting of soil detachment and transport by raindrop impact and surface flow, localized deposition due to topography, and tillage-induced roughness as well as rainwater infiltration into the soil profile. Values for *K* factor typically range from about 0.05 to 0.45 with high-sand and high-clay content soils having the lower values and high-silt content soils having the higher values. *K* factors can be determined from direct measurements on natural runoff plots, with empirical equations, a USDA soil nomograph, or from general soil-type classifications such as produced by the Soil Conservation Service (SCS, 1993). *K* factors used in this study were determined from direct measurements, reported from each laboratory or when these data were not provided, the general soil chart presented in Table 2.2 was utilized based on quantity of organic matter.

Table 2.2 – Textural class *K* factor table (from the SCS (1993))

Textural class	Average	Less than 2%	More than 2%
clay	0.22	0.24	0.21
clay loam	0.30	0.33	0.28
coarse sandy loam	0.07	–	0.07
fine sand	0.08	0.09	0.06
fine sandy loam	0.18	0.22	0.17
heavy clay	0.17	0.19	0.15
loam	0.30	0.34	0.26
loamy fine sand	0.11	0.15	0.09
loamy sand	0.04	0.05	0.04
loamy very fine sand	0.39	0.44	0.25
sand	0.02	0.03	0.01
sandy clay loam	0.20	–	0.20
sandy loam	0.13	0.14	0.12
silt loam	0.38	0.41	0.37
silty clay	0.26	0.27	0.26
silty clay loam	0.32	0.35	0.30
very fine sand	0.43	0.46	0.37
very fine sandy loam	0.35	0.41	0.33

2.4.4 *L* and *S* Factors

L factor is the slope-length factor, which is the ratio of soil loss from the slope length measured in the field to that from a 72.6-ft length on the same soil type and gradient. *S* factor is the slope-steepness factor, which is the ratio of soil loss from the slope found to that from a 9% slope under the same conditions and is the distance from the start of overland flow to the point where concentrated flow or deposition occurs. *L* and *S* factors can be computed from empirical equations as:

$$L\text{ factor} = \left(\frac{\lambda}{72.6}\right)^m \quad \textbf{Eq. (2.9)}$$

where

λ = horizontal slope length (ft);

72.6 = RUSLE unit plot length (ft); and

m = variable slope-length exponent.

The slope-length exponent (m) is related to the ratio (β) of rill erosion caused by flow to interrill erosion caused by raindrop impact with the following equation:

$$m = \frac{\beta}{(1+\beta)} \quad \textbf{Eq. (2.10)}$$

Values for the ratio β of rill to interrill erosion for conditions when the soil is moderately susceptible to both rill and interrill erosion were computed from McCool *et al*. (1989):

$$\beta = \frac{(\sin\Theta / 0.0896)}{\left[3.0(\sin\Theta)^{0.8} + 0.56\right]} \quad \textbf{Eq. (2.11)}$$

where

Θ = slope angle.

Slope-steepness factor (S) is evaluated from McCool *et al*. (1987) for non-thawing soils as:

S factor = 10.8 sin Θ + 0.03 for slopes less than 5 degrees **Eq. (2.12)**

S factor = 16.8 sin Θ – 0.50 for slopes equal to or greater than 5 degrees **Eq. (2.13)**

And for thawing soils:

S factor = 10.8 sin Θ + 0.03 for slopes less than 5 degrees **Eq. (2.14)**

$$S \text{ factor} = \left(\frac{\sin\Theta}{0.0896}\right)^{0.6}$$ for slopes equal to or greater than 5 degrees **Eq. (2.15)**

2.4.5 *C* Factor

Cover management is examined by the RUSLE via the *C* factor. *C* factor represents the effect of surface cover and roughness on soil erosion. *C* factor is the most common factor used to assess the impact of best management practices (BMPs) on reducing erosion due to the fact that the *C* factor represents the effect of land use on soil erosion (Renard *et al*., 1997). Values for *C* factor range from zero imply non-erodibly to values that can be greater than 1.0. Values greater than 1.0 imply conditions more erodible than those normally experienced under unit plot conditions. For example, a smooth compact soil surface would be considered to have a *C* factor of approximately 1.2, whereas, grass sod would be considered to have a *C* factor of approximately 0.01. *C* factor can be determined from prior land use subfactors as described in *Agriculture Handbook Number 703* (USDA, 1997) or by large-scale laboratory testing. The *C* factor for this study was assumed to be 1.0 for all analyses, since the data were for bare-soil conditions only.

2.4.6 *P* Factor

P factor represents how surface conditions affect flow paths and flow hydraulics (Renard *et al*., 1994). For example, with contouring present, runoff flows around the slope in channels formed by tillage. Other examples of conditions for *P* factors are stripcropping and terracing. The *P* factor for this study was assumed to be 1.0 for all analyses, since there were no additional surface conditions present during the testing.

2.5 Summary

This chapter has presented information on why large-scale rainfall testing laboratories are needed, what the necessary key rainfall testing parameters are for proper modeling, and a discussion on the most widely-utilized prediction model used to link laboratory data to field implementation that impacts construction site design and USEPA requirements. In particular, the RUSLE is applied at laboratory scale using some of the key rainfall testing parameters to determine key erosion parameters that are used on construction sites to meet USEPA requirements. On the surface, the application of the RUSLE at the laboratory scale appears to make good sense due to the simplicity of use and ease of determining the necessary parameters. However, based on the limitation that the RUSLE was not intended to predict individual storm events and the fact that it only accounts for eight of the key paramaters, the question of proper application for the RUSLE at the laboratory scale becomes the basis for this dissertation. Therefore, the RUSLE equation will be checked against a broad set of data from various laboratories as well as compared against a new erosion-prediction equation to examine the validity of application on construction sites using laboratory-generated *C* factor data.

3 DATABASE

3.1 Introduction

Bare-soil rainfall erosion data were obtained from five commonly-utilized large-scale testing facilities. Data were obtained from these facilities: 1) ErosionLab® in Wisconsin (Clopper *et al*., 2001; Kelsey, 2002; Early *et al*., 2003); 2) San Diego State University in California (Beighley, 2011, pers. comm.); 3) Texas Research International/Environmental in South Carolina (Profile® Products LLC, 2007-2011); 4) Texas Transportation Institute in Texas (Foster and McFalls, 2011, pers. comm.); and 5) Utah State University in Utah (Profile® Products LLC, 1999-2011). Twenty-five sets of bare-soil testing data were obtained, with a total of sixty-eight unique data points and fourteen common variables that were obtained from each facility. Table 3.1 displays the common variables obtained from each laboratory, a brief description, an overview of the range, and the units. Table 3.2 presents a complete listing of the sixty-eight data points obtained from the various laboratories.

Table 3.1 – List of common variables available from each laboratory

Parameter	Description	Range	Units
SL	soil loss	0 – 846	tons/acre
I	rainfall intensity	1.7 – 7.4	in./hr
A	plot area	0.0018 – 0.0074	acres
T	test duration	0.33 – 1.5	hrs
S	slope gradient	0.25 – 0.5	decimal %
RD_{50}	median raindrop size	2 – 4	mm
KE	raindrop kinetic energy	1.7 – 21.2	ft-poundal*1,000
% sand	percent sand	0.01 – 0.84	decimal %
% silt	percent silt	0.03 – 0.62	decimal %
% clay	percent clay	0.01 – 0.38	decimal %
% compacted	surface compaction percentage	0.71 – 0.89	decimal %
PL	plastic limit	0 – 0.28	decimal %
PI	plasticity index	0 – 0.19	decimal %
LL	liquid limit	0 – 0.32	decimal %

Table 3.2 – Complete listing of data obtained from each laboratory

Event	Cumulative soil loss (tons/acre)	Rainfall intensity (in./hr)	Plot area (acres)	Test duration (hrs)	Slope gradient (ft/ft)	Median raindrop size (mm)	Raindrop kinetic energy (ft-poundal *1,000)	*% sand*	*% silt*	*% clay*	*% compacted*	Plastic limit	Plasticity index	Liquid limit
1	10.7	1.9	0.0040	0.33	0.45	2.3	3.5	0.82	0.18	0.01	0.75	0.18	0.04	0.22
2	82.1	3.7	0.0040	0.33	0.45	2.3	3.5	0.82	0.18	0.01	0.75	0.18	0.04	0.22
Final	273.1	6.3	0.0040	0.33	0.45	2.3	3.5	0.82	0.18	0.01	0.75	0.18	0.04	0.22
1	0.1	2.3	0.0073	0.33	0.33	2.0	1.7	0.65	0.24	0.11	0.77	0.28	0.04	0.32
2	8.0	4.3	0.0073	0.33	0.33	2.0	1.7	0.65	0.24	0.11	0.77	0.28	0.04	0.32
Final	24.7	5.5	0.0073	0.33	0.33	2.0	1.7	0.65	0.24	0.11	0.77	0.28	0.04	0.32
1	1.8	2.0	0.0073	0.33	0.33	2.3	2.6	0.44	0.30	0.11	0.75	0.20	0.05	0.24
2	44.6	5.6	0.0073	0.33	0.33	2.3	2.6	0.44	0.30	0.11	0.75	0.20	0.05	0.24
Final	118.2	7.4	0.0073	0.33	0.33	2.3	2.6	0.44	0.30	0.11	0.75	0.20	0.05	0.24
1	30.0	5.0	0.0018	0.50	0.40	4.0	21.2	0.6	0.28	0.12	0.72	0.05	0.185	0.234
Final	110.9	5.0	0.0018	0.50	0.40	4.0	21.2	0.6	0.28	0.12	0.72	0.05	0.185	0.234
1	19.4	3.5	0.0041	0.50	0.33	3.5	13.4	0.44	0.16	0.38	0.89	0.05	0.185	0.234
2	38.8	3.5	0.0041	0.50	0.33	3.5	13.4	0.44	0.16	0.38	0.89	0.05	0.185	0.234
Final	58.2	3.5	0.0041	0.50	0.33	3.5	13.4	0.44	0.16	0.38	0.89	0.05	0.185	0.234
1	0.0	1.8	0.0073	0.33	0.33	2.0	1.7	0.65	0.24	0.11	0.77	0.28	0.04	0.32
2	4.7	2.9	0.0073	0.33	0.33	2.0	1.7	0.65	0.24	0.11	0.77	0.28	0.04	0.32
Final	16.6	4.6	0.0073	0.33	0.33	2.0	1.7	0.65	0.24	0.11	0.77	0.28	0.04	0.32
1	1.5	2.3	0.0073	0.33	0.33	2.3	2.6	0.44	0.30	0.11	0.75	0.20	0.05	0.24
2	43.6	4.4	0.0073	0.33	0.33	2.3	2.6	0.44	0.30	0.11	0.75	0.20	0.05	0.24
Final	97.1	5.6	0.0073	0.33	0.33	2.3	2.6	0.44	0.30	0.11	0.75	0.20	0.05	0.24
1	9.6	1.9	0.0040	0.33	0.33	2.3	3.5	0.82	0.18	0.01	0.75	0.18	0.04	0.22
2	78.3	3.7	0.0040	0.33	0.33	2.3	3.5	0.82	0.18	0.01	0.75	0.18	0.04	0.22
Final	239.0	6.3	0.0040	0.33	0.33	2.3	3.5	0.82	0.18	0.01	0.75	0.18	0.04	0.22
1	37.6	5.0	0.0018	0.50	0.40	4.0	21.2	0.6	0.28	0.12	0.72	0.05	0.185	0.234
Final	89.3	5.0	0.0018	0.50	0.40	4.0	21.2	0.6	0.28	0.12	0.72	0.05	0.185	0.234
1	12.7	1.9	0.0040	0.33	0.25	2.3	3.5	0.82	0.18	0.01	0.75	0.18	0.04	0.22
2	69.2	3.7	0.0040	0.33	0.25	2.3	3.5	0.82	0.18	0.01	0.75	0.18	0.04	0.22
Final	192.5	6.3	0.0040	0.33	0.25	2.3	3.5	0.82	0.18	0.01	0.75	0.18	0.04	0.22
1	21.6	3.5	0.0041	0.50	0.50	3.5	13.4	0.44	0.16	0.38	0.89	0.05	0.185	0.234
2	43.1	3.5	0.0041	0.50	0.50	3.5	13.4	0.44	0.16	0.38	0.89	0.05	0.185	0.234
Final	64.7	3.5	0.0041	0.50	0.50	3.5	13.4	0.44	0.16	0.38	0.89	0.05	0.185	0.234
1	3.3	2.1	0.0073	0.33	0.33	2.3	2.6	0.44	0.30	0.11	0.75	0.20	0.05	0.24
2	73.9	4.3	0.0073	0.33	0.33	2.3	2.6	0.44	0.30	0.11	0.75	0.20	0.05	0.24
Final	126.6	5.4	0.0073	0.33	0.33	2.3	2.6	0.44	0.30	0.11	0.75	0.20	0.05	0.24
1	33.5	5.0	0.0018	0.50	0.40	4.0	21.2	0.6	0.28	0.12	0.72	0.05	0.185	0.234
Final	179.5	5.0	0.0018	0.50	0.40	4.0	21.2	0.6	0.28	0.12	0.72	0.05	0.185	0.234

Event	Cumulative soil loss (tons/acre)	Rainfall intensity (in./hr)	Plot area (acres)	Test duration (hrs)	Slope gradient (ft/ft)	Median raindrop size (mm)	Raindrop kinetic energy (ft-poundal *1,000)	*% sand*	*% silt*	*% clay*	*% compacted*	Plastic limit	Plasticity index	Liquid limit
1	88.2	7.0	0.0018	0.50	0.40	4.0	21.2	0.6	0.28	0.12	0.72	0.05	0.185	0.234
Final	313.2	7.0	0.0018	0.50	0.40	4.0	21.2	0.6	0.28	0.12	0.72	0.05	0.185	0.234
1	124.1	3.5	0.0041	0.50	0.33	3.5	13.4	0.84	0.04	0.12	0.71	0.02	0.16	0.18
2	248.3	3.5	0.0041	0.50	0.33	3.5	13.4	0.84	0.04	0.12	0.71	0.02	0.16	0.18
Final	372.4	3.5	0.0041	0.50	0.33	3.5	13.4	0.84	0.04	0.12	0.71	0.02	0.16	0.18
1	6.4	2.0	0.0040	0.33	0.33	2.3	3.5	0.82	0.18	0.01	0.75	0.18	0.04	0.22
2	57.2	3.5	0.0040	0.33	0.33	2.3	3.5	0.82	0.18	0.01	0.75	0.18	0.04	0.22
Final	170.4	6.3	0.0040	0.33	0.33	2.3	3.5	0.82	0.18	0.01	0.75	0.18	0.04	0.22
1	20.0	5.0	0.0018	0.50	0.40	4.0	21.2	0.6	0.28	0.12	0.88	0.05	0.185	0.234
Final	45.7	5.0	0.0018	0.50	0.40	4.0	21.2	0.6	0.28	0.12	0.88	0.05	0.185	0.234
1	2.2	1.8	0.0073	0.33	0.33	2.3	2.6	0.44	0.30	0.11	0.75	0.20	0.05	0.24
2	54.1	4.9	0.0073	0.33	0.33	2.3	2.6	0.44	0.30	0.11	0.75	0.20	0.05	0.24
Final	114.0	6.9	0.0073	0.33	0.33	2.3	2.6	0.44	0.30	0.11	0.75	0.20	0.05	0.24
1	0.0	2.4	0.0073	0.33	0.33	2.0	1.7	0.65	0.24	0.11	0.77	0.28	0.04	0.32
2	11.1	4.6	0.0073	0.33	0.33	2.0	1.7	0.65	0.24	0.11	0.77	0.28	0.04	0.32
Final	25.0	6.3	0.0073	0.33	0.33	2.0	1.7	0.65	0.24	0.11	0.77	0.28	0.04	0.32
1	22.6	5.0	0.0018	0.50	0.40	4.0	21.2	0.6	0.28	0.12	0.88	0.05	0.185	0.234
Final	46.1	5.0	0.0018	0.50	0.40	4.0	21.2	0.6	0.28	0.12	0.88	0.05	0.185	0.234
1	11.7	2.0	0.0040	0.33	0.33	2.3	3.5	0.82	0.18	0.01	0.75	0.18	0.04	0.22
2	72.5	3.5	0.0040	0.33	0.33	2.3	3.5	0.82	0.18	0.01	0.75	0.18	0.04	0.22
Final	187.5	6.3	0.0040	0.33	0.33	2.3	3.5	0.82	0.18	0.01	0.75	0.18	0.04	0.22
1	282.1	3.5	0.0041	0.50	0.50	3.5	13.4	0.84	0.04	0.12	0.71	0.02	0.16	0.18
2	564.1	3.5	0.0041	0.50	0.50	3.5	13.4	0.84	0.04	0.12	0.71	0.02	0.16	0.18
Final	846.2	3.5	0.0041	0.50	0.50	3.5	13.4	0.84	0.04	0.12	0.71	0.02	0.16	0.18
1	0.0	2.9	0.0073	0.33	0.33	2.0	1.7	0.65	0.24	0.11	0.77	0.28	0.04	0.32
2	9.5	5.3	0.0073	0.33	0.33	2.0	1.7	0.65	0.24	0.11	0.77	0.28	0.04	0.32
Final	21.7	5.9	0.0073	0.33	0.33	2.0	1.7	0.65	0.24	0.11	0.77	0.28	0.04	0.32
1	1.2	1.7	0.0073	0.33	0.33	2.3	2.6	0.01	0.62	0.37	0.75	0.21	0.10	0.31
2	14.7	4.5	0.0073	0.33	0.33	2.3	2.6	0.01	0.62	0.37	0.75	0.21	0.10	0.31
Final	43.9	6.5	0.0073	0.33	0.33	2.3	2.6	0.01	0.62	0.37	0.75	0.21	0.10	0.31
1	16.4	5.0	0.0018	0.50	0.40	4.0	21.2	0.6	0.28	0.12	0.88	0.05	0.185	0.234
Final	35.4	5.0	0.0018	0.50	0.40	4.0	21.2	0.6	0.28	0.12	0.88	0.05	0.185	0.234

3.2 Laboratory Testing Procedures

Testing procedures at each laboratory were similar. Each laboratory had a defined soil type that was installed according to typical soil placement techniques; which included placing soil in lifts of 4 to 6 in. and compacting to varying levels, and producing a finished surface. Each plot was separated by metal flashing. Each facility had rainfall calibration data for intensity on file that was used for rainfall setup. All of the testing data obtained were for bare-soil testing conditions, so once the soil surfaces were prepared, each of the facilities then applied rainfall according to how their rainfall simulators were setup (i.e., nozzle, sprinkler, or drip). Each facility performed the rainfall event for a minimum of 60 min, some were performed with two or three 30-min events back-to-back and others were performed with three 20-min events back-to-back to achieve the desired time. At each interval (either 20 or 30 min), the total amount of soil and water from each plot was collected and the total amount of soil loss was reported.

3.3 Discussion of Database

Based on the information presented in the literature review on key rainfall parameters, it appears that the common information that was obtained from each of the laboratories provides a significant portion of the key parameters. In particular, of the nineteen key parameters that should be measured and reported, fourteen of the variables were obtained from the laboratories. The variables that were not available from all laboratories were: organic content of the soil, underlying compaction percentage, soil permeability, water volumes over time, and turbidity. With the major objective of this study to develop a unifying soil-loss predictive relationship, an adequate amount of the key testing parameters are available for a comprehensive analysis, with nearly 75% of the key data parameters being available.

4 DATA ANALYSIS

4.1 Introduction

A detailed analysis of the database obtained from the various laboratories was needed to determine how to best proceed. An examination of how the data compared when examined with the use of the RUSLE was perfomed. Following the RUSLE application, a discussion of how the database should be analysed was performed, along with a method for determination of which variables from the database to use for developing a new predictive relationship. Next, a thorough review of the statistics that were needed to develop the new predictive relationship were presented followed by development of a new predictive relationship.

4.2 RUSLE Examination

The existing prediction equation commonly utilized to determine cover factors as recommended by the USEPA and for analysis in the large-scale testing facilities is the RUSLE equation as presented in Section 2.4.1. An examination of how effective the RUSLE equation predicts the bare-soil loss compared to the sixty-eight reported bare-soil loss values was presented. The individual values for the RUSLE are presented in Table 4.1.

Table 4.1 – RUSLE data

Observed cumulative soil loss (tons/acre)	Factors					Predicted soil loss (tons/acre)
	Cumulative R^a	K^b	LS	C	P	
10.7	12.4	0.10	2.98515	1	1	3.7
82.1	62.2	0.10	2.98515	1	1	18.6
273.1	207.6	0.10	2.98515	1	1	62.0
0.1	17.8	0.24	3.12017	1	1	13.3
8.0	85.3	0.24	3.12017	1	1	63.9
24.7	194.0	0.24	3.12017	1	1	145.3
1.8	14.2	0.30	3.12017	1	1	13.3
44.6	129.5	0.30	3.12017	1	1	121.2
118.2	329.1	0.30	3.12017	1	1	308.0

Observed cumulative soil loss (tons/acre)	Factors					Predicted soil loss (tons/acre)
	Cumulative R^a	K^b	*LS*	*C*	*P*	
30.0	137.2	0.24	2.221	1	1	73.1
110.9	274.4	0.24	2.221	1	1	146.3
19.4	66.7	0.25	2.57467	1	1	43.0
38.8	133.5	0.25	2.57467	1	1	85.9
58.2	200.2	0.25	2.57467	1	1	128.9
0.0	11.0	0.24	3.12017	1	1	8.2
4.7	41.3	0.24	3.12017	1	1	30.9
16.6	116.9	0.24	3.12017	1	1	87.6
1.5	18.3	0.30	3.12017	1	1	17.2
43.6	89.1	0.30	3.12017	1	1	83.4
97.1	204.3	0.30	3.12017	1	1	191.2
9.6	12.4	0.10	2.35477	1	1	2.9
78.3	62.2	0.10	2.35477	1	1	14.6
239.0	207.6	0.10	2.35477	1	1	48.9
37.6	137.2	0.24	2.221	1	1	73.1
89.3	274.4	0.24	2.221	1	1	146.3
12.7	12.4	0.10	1.8291	1	1	2.3
69.2	62.2	0.10	1.8291	1	1	11.4
192.5	207.6	0.10	1.8291	1	1	38.0
21.6	66.7	0.25	3.49294	1	1	58.3
43.1	133.5	0.25	3.49294	1	1	116.6
64.7	200.2	0.25	3.49294	1	1	174.9
3.3	15.3	0.30	3.12017	1	1	14.4
73.9	83.2	0.30	3.12017	1	1	77.9
126.6	188.2	0.30	3.12017	1	1	176.1
33.5	137.2	0.24	2.221	1	1	73.1
179.5	274.4	0.24	2.221	1	1	146.3
88.2	269.2	0.24	2.221	1	1	143.5
313.2	538.5	0.24	2.221	1	1	287.0
124.1	66.7	0.08	2.57467	1	1	13.7
248.3	133.5	0.08	2.57467	1	1	27.5
372.4	200.2	0.08	2.57467	1	1	41.2
6.4	13.8	0.10	2.35477	1	1	3.3
57.2	58.3	0.10	2.35477	1	1	13.7
170.4	203.7	0.10	2.35477	1	1	48.0
20.0	137.2	0.24	2.221	1	1	73.1
45.7	274.4	0.24	2.221	1	1	146.3
2.2	10.6	0.30	3.12017	1	1	9.9
54.1	97.4	0.30	3.12017	1	1	91.1
114.0	272.3	0.30	3.12017	1	1	254.8
0.0	19.5	0.24	3.12017	1	1	14.6
11.1	96.8	0.24	3.12017	1	1	72.5
25.0	239.9	0.24	3.12017	1	1	179.7
22.6	137.2	0.24	2.221	1	1	73.1
46.1	274.4	0.24	2.221	1	1	146.3
11.7	13.8	0.10	2.35477	1	1	3.3

Observed cumulative soil loss (tons/acre)	Factors					Predicted soil loss (tons/acre)
	Cumulative R[a]	K[b]	LS	C	P	
72.5	58.3	0.10	2.35477	1	1	13.7
187.5	203.7	0.10	2.35477	1	1	48.0
282.1	66.7	0.08	3.49294	1	1	18.7
564.1	133.5	0.08	3.49294	1	1	37.3
846.2	200.2	0.08	3.49294	1	1	56.0
0.0	29.2	0.24	3.12017	1	1	21.9
9.5	130.1	0.24	3.12017	1	1	97.4
21.7	257.5	0.24	3.12017	1	1	192.8
1.2	9.7	0.32	3.12017	1	1	9.7
14.7	82.9	0.32	3.12017	1	1	82.8
43.9	235.3	0.32	3.12017	1	1	234.9
16.4	137.2	0.24	2.221	1	1	73.1
35.4	274.4	0.24	2.221	1	1	146.3

[a]As computed from equations in Section 2.4.1
[b]From textural table (Table 2.1) or as reported from each laboratory

Figure 4.1 presents the data in graphic form of observed cumulative soil loss versus RUSLE predicted soil loss. In order to compare these data to information presented later in the document, the soil-loss values were presented as the log of the soil loss. As can be observed in Figure 4.1, the RUSLE utilized for large-scale laboratory analysis for American Society for Testing and Materials (ASTM, 2007) D6459 does not adequately predict the observed bare-soil loss across multiple laboratories. The line of equal fit is shown in Figure 4.1 and if the RUSLE adequately predicted the bare-soil loss across multiple large-scale laboratories, most of the points would fall near the equal fit line. The RUSLE, when applied to the bare-soil data sets from all of the various laboratories, overpredicts by as much as 1,045% and underpredicts by as much as 93%. Any equation that has a prediction spread ranging from underprediction of 55% and overprediction of over 1,000% should not be utilized. Further, as can be seen in Figure 4.1, for the observed value of 1, the predicted value was anywhere from 0.5 to 2.0, which is an error as much as 100%. Therefore, a better prediction equation is needed.

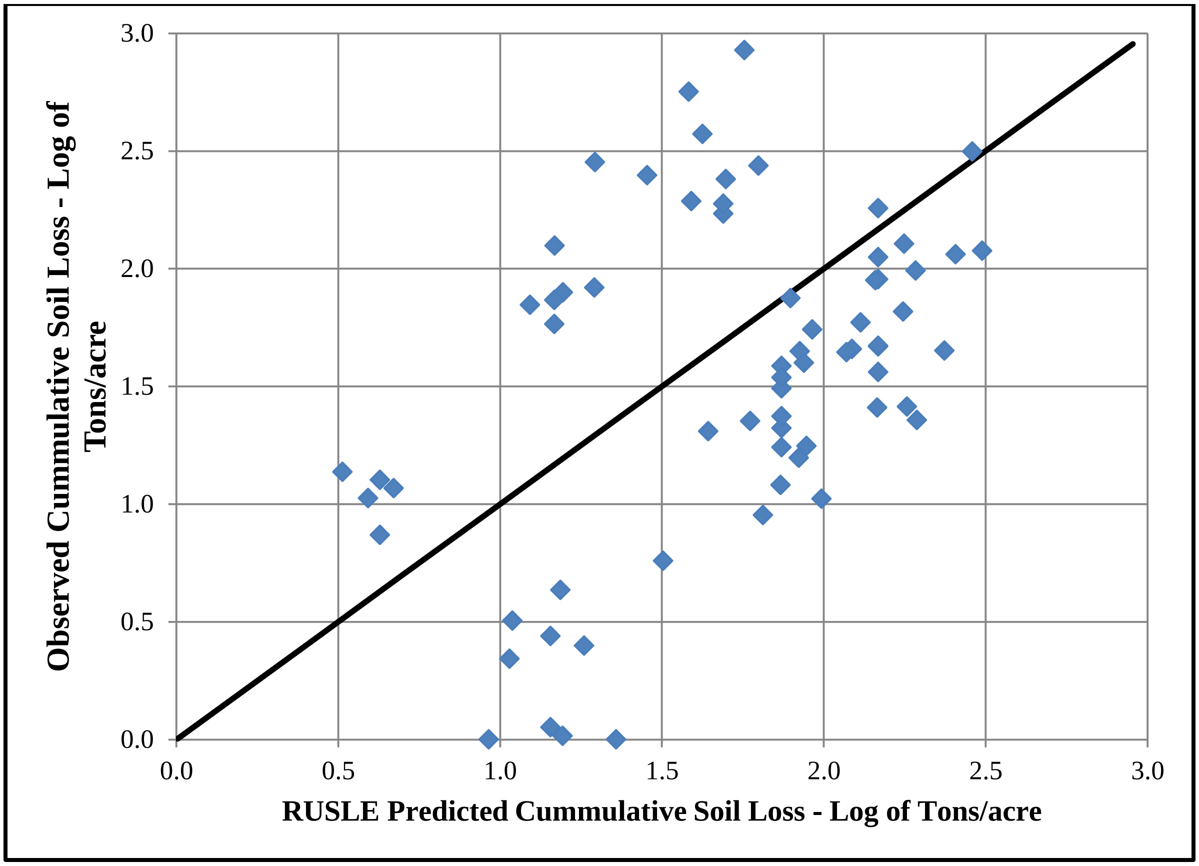

Figure 4.1 – Plot of RUSLE predicted soil loss versus observed soil loss

To examine some of the differences and contributions between each laboratory, Figure 4.1 was reproduced using different symbols for each of the five laboratories, as is shown in Figure 4.2.

As can be observed in Figure 4.2, when the RUSLE is applied to laboratory data, the result for Labs B, C, D, and E1 is an overprediction of soil-loss values by anywhere from 16 (Lab D) to 50% (Lab B). Whereas, RUSLE results for Labs A and E2 are underpredicted anywhere from 30 (Lab A) to 70% (Lab E2). In the end, it appears that the use of the RUSLE at the laboratory scale at any laboratory will lead to rather significant errors, with the use of RUSLE at Lab D being the closest to the observed values with an average overprediction of 16%.

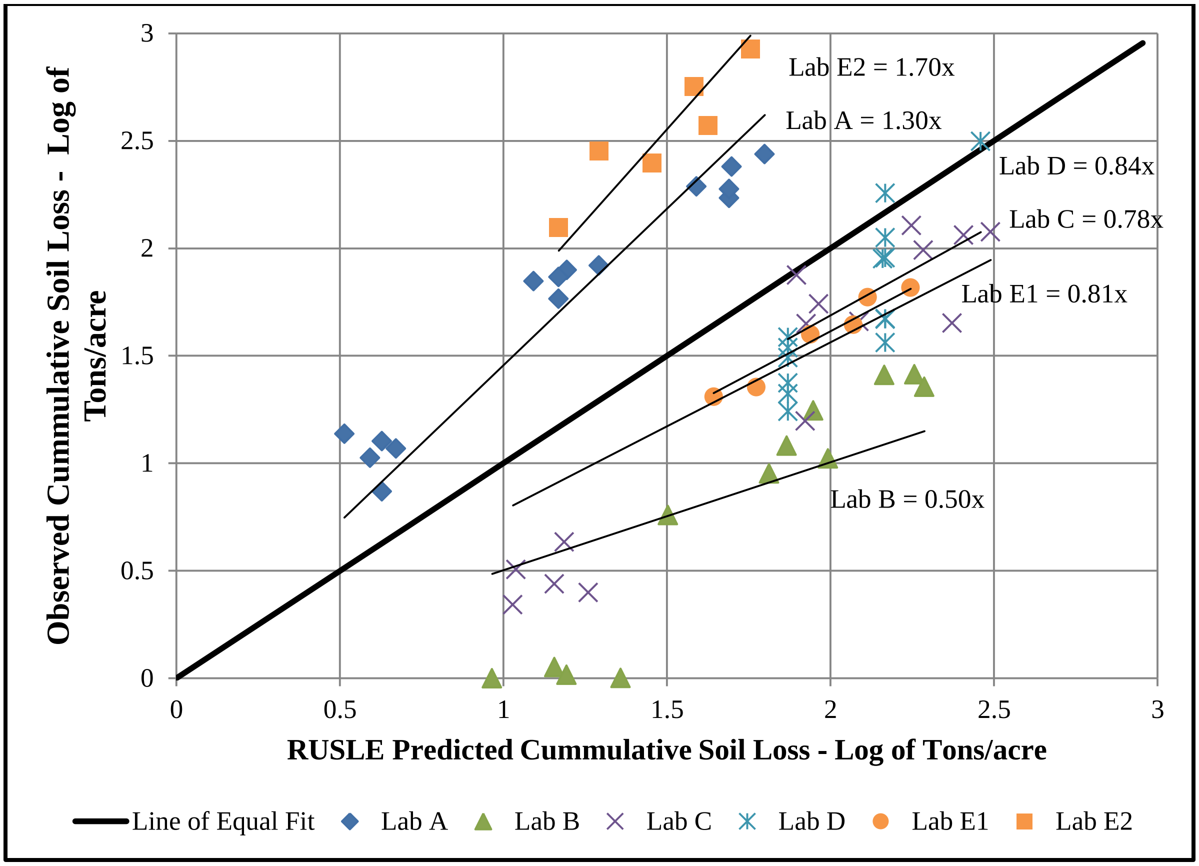

Figure 4.2 – Plot of RUSLE predicted soil loss versus observed soil loss for each laboratory

4.3 Database Examination

Based on the previous discussion, it has become clear that the application of the RUSLE at the laboratory scale does not produce reliable results, therefore, the database will be used to develop a new predictive equation. Data analysis for developing a multiple large-scale laboratory soil-loss prediction equation can be accomplished by performing a statistical variable selection in conjunction with an understanding of the physical processes to determine the variables that are most significant for developing a predictive relationship. Once the appropriate variables have been selected, statistical analysis with applied regression techniques can be implemented to develop relationships between soil loss and the chosen independent variables.

Subsequent sections discuss the variable selection and statistical analyses performed under the scope of this study.

4.4 Variable Selection

In order to determine which variables to use for the development of the soil-loss prediction equation, a statistical analysis tool called *standardized coefficients* was utilized as determined after consultation with a Statistics professor, Jim zumBrunnen, at Colorado State University. Standardized coefficients are the estimates resulting from an analysis carried-out on variables that have been standardized so that their variances are 1. Therefore, standardized coefficients refer to how many standard deviations a dependent variable will change, per standard deviation increase in the predictor variable (Nisbet *et al*., 2009). Standardization of the coefficient anaylsis can be performed to answer the question: Which of the independent variables have a greater effect on the dependent variable in a multiple-regression analysis? The results of the standarized coefficient analysis which employed best subsets, forward stepwise, backward stepwise, forward entry, and backward removal discriminate techniques. Prior to the analysis, it was determined after consultation with Jim zumBrunnen, that the dependent variable (soil loss) required a log plus 1 transformation to normalize the data due to the fact that several of the observed soil-loss values were either at zero or approximately zero. After the log transformation of the dependent variable (cumulative soil loss), the standardized coefficients analysis was performed using Statistica 10 (StatSoft®, 2011). The standardized coefficient analysis resulted in the information plotted in Figure 4.3.

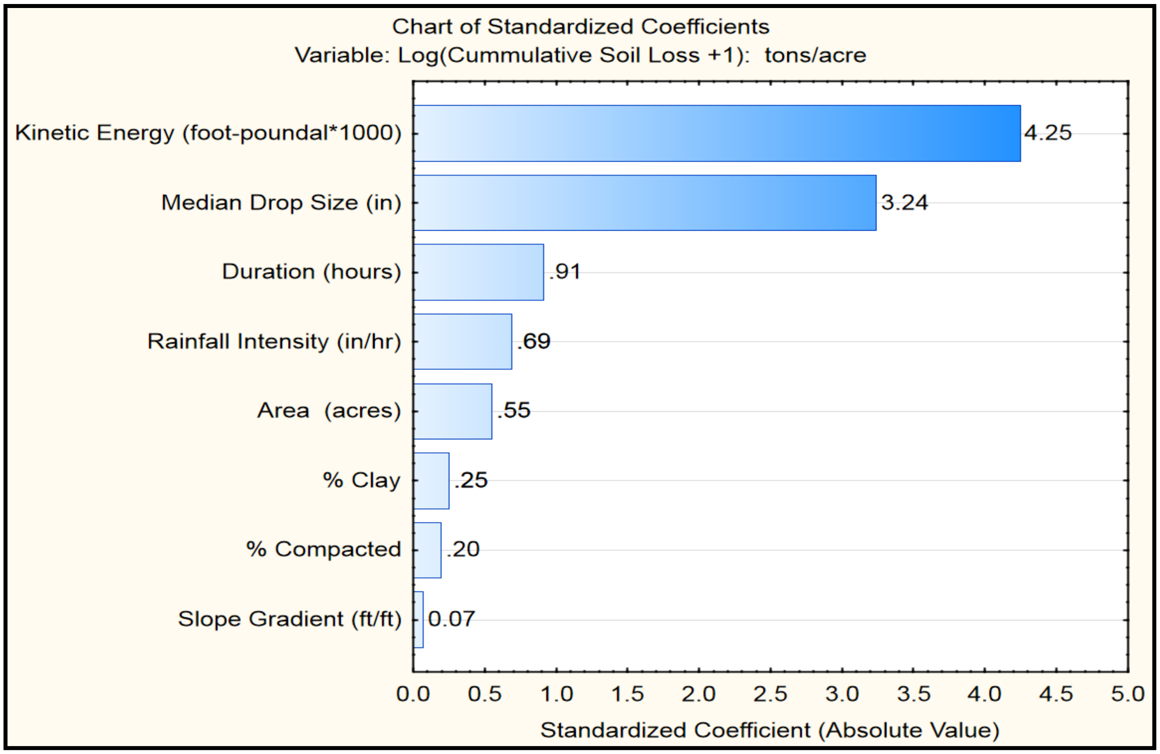

Figure 4.3 – Plot of standardized coefficient analysis

Figure 4.3 shows the eight significant variables out of the thirteen independent variables available from the database, noting that soil loss was chosen as the independent variable. In addition, Figure 4.3 shows relative significance of each of the significant variables. In particular, the analysis and resulting data shown in Figure 4.3, show that kinetic energy, median drop size, and duration are the three strongest predictor variables followed by rainfall intensity and plot area, percentage of clay, percent compacted, and then slope gradient. The other five independent variables from the initial database had standardized coefficients that were considered not significant. Further, from a physics perspective, the eight variables presented above represent the major key parameters as presented in Section 2.3 that are typically associated with soil-loss prediction. In particular, this analysis confirms that kinetic energy is the most significant parameter for predicting rainfall-induced erosion. Of the variables that were selected, the RUSLE does not account for the raindrop kinetic energy, raindrop size, event duration, percentage of surface compaction, or the plot width; which could explain why RUSLE does not do an adequate job of predicting soil loss for individual rainfall events at the laboratory scale.

4.5 Statistical Analysis

Statistical analysis employed in this data analysis incorporated the principle of least squares and multivariate linear regression. The principle of least squares can be applied to one dependent variable and one independent variable, or to one dependent and several independent variables. When more than one independent variable has been introduced, then a multivariate linear-regression analysis becomes necessary. Subsequent sections discuss the statistical theory and assumptions used for analysis in this study.

4.5.1 Statistical Theory

Regression analysis involves an area of statistics that provides methods to investigate the existence of associations and, if present, the nature of the associations, among various observable quantities (Graybill and Iyer, 1994). A commonly-used method for obtaining a prediction function for predicting the values of a response variable Y using predictor variables $X_1,\ldots..,X_k$, utilizes the principle of least squares.

A definition of the principle of least squares was first introduced by the German mathematician Gauss who stated that a line provides a good fit to a series of data if the vertical distances (deviations) from the observed point to the line are small (Devore, 1995). Devore (1995) further stated that a measure of the goodness-of-fit can be expressed as the sum of the squares of individual deviations. Therefore, the line having the smallest possible sum of squared deviations would be the best-fit line. Eq. (4.1) mathematically expresses the principle of least squares:

$$f(\beta_0,...,\beta_k) = \sum_{i=1}^{n}\left[Y_i - \left(\beta_0 + \beta_1 X_{1i} + ... + \beta_k X_{ki}\right)\right]^2$$ **Eq. (4.1)**

where

β_0	=	y-intercept of the linear relationship;
β_k	=	slope of the regression line for the k^{th} independent variable;
Y_i	=	value of a measured data point;
$\beta_0 + \beta_1 X_{1i} + ... + \beta_k X_{ki}$	=	equation of the regression line; and

all other variables are defined previously.

Least squares estimates for the y-intercept and slope of the regression lines are found by minimizing $f(\beta_0,\beta_1,...,\beta_k)$. Values β_0 through β_k are minimized by taking partial derivatives of $f(\beta_0,\beta_1,...,\beta_k)$ with respect to all βs and then setting them equal to zero. All equations can then be solved for the least squares estimates of the coefficients ($\beta_0,\beta_1,...,\beta_k$) for the estimated regression line.

Statistical analysis of the data in these experiments incorporated techniques of multivariate linear regression. A general additive multivariate regression model equation can be expressed as:

$$Y = \beta_0 = \beta_1 X_1 + \beta_2 X_2 + ... + \beta_k X_k + \varepsilon$$ **Eq. (4.2)**

where

Y	=	dependent variable;
X_k	=	k^{th} independent variable;
ε	=	random deviation or random error; and

all other variables are defined previously.

Random deviation or random error (ε) can be assumed to be normally distributed with $E(\varepsilon) = 0$ and $V(\varepsilon) = \sigma^2$. Values of $E(\varepsilon)$ and $V(\varepsilon)$ are the mean and variance of the random deviation or random error, respectively. As $E(\varepsilon)$ and $V(\varepsilon)$ become small, any observations of the dependent variables approach the true regression line. When the value of ε exceeds zero, the actual data point falls above the regression line and will be higher than the predicted value. Similarly, when ε does not reach zero, the actual data point falls below the regression line and will be lower than the predicted value.

Goodness-of-fit, or quality of the regression analysis, can be measured through the variance (σ^2) of the regression model or the mean squared error (MSE). Variance (σ^2) can be computed through the error sum of squares (SSE) with the following relationship:

$$\sigma^2 = \frac{\sum_{i=1}^{n}\left(Y_i - \hat{\beta}_0 - \hat{\beta}_1 X_{1i} - ..... - \hat{\beta}_k X_{ki}\right)^2}{n-k-1} = \frac{SSE}{n-k-1} = MSE \qquad \textbf{Eq. (4.3)}$$

Values of n-k-1 in the denominator of Eq. (4.3) represent the number of degrees-of-freedom associated with the error sum of squares (SSE). Another way to think about SSE would be to use it as a measure of how much variation in the dependent variable (Y) cannot be explained by the model.

Coefficient of determination (R^2) proves to be another measure of goodness-of-fit, or quality of the regression analysis model. R^2 can be determined using SSE and the total sum of squares (SSY). SSY computes as follows:

$$SSY = \sum_{i=1}^{n}\left(Y_i - \overline{Y}\right)^2 \qquad \textbf{Eq. (4.4)}$$

$\overline{Y}$ = mean of the dependent variable Y; and all other variables are defined previously.

Total sum of squares (*SSY*) measures the variability of the actual value of Y_i measured about the mean of the dependent variable *Y*. R^2 calculates as:

$$R^2 = 1 - \frac{SSE}{SSY} \qquad \textbf{Eq. (4.5)}$$

R^2 measures the variation in the dependent variable (*Y*) that can be explained by the bivariate or multivariate linear-regression model.

After the completion of a multivariate linear regression, a display of the overall summary of a multivariate linear-regression analysis should be presented. An overall summary can be presented with the analysis of variance (ANOVA) as depicted in Table 4.2. Important terms for an ANOVA, the sum of squares due to regression (*SSR*) as well as the mean square due to regression (*MSR*), can both be computed as follows:

$$SSR = SSY - SSE \qquad \textbf{Eq. (4.6)}$$

$$MSR = \frac{SSR}{k} \qquad \textbf{Eq. (4.7)}$$

Table 4.2 – Example of quantities often shown in an ANOVA table

Source	Degrees-of-freedom (*df*)	Sum of squares (*SS*)	Mean square (*MS*)	F-statistic	p-level
regression	k	*SSR*	*MSR*	*MSR/MSE*	$p < .05$
residual error	n-k-1	*SSE*	*MSE*		
total	n-1	*SSY*			

Once a fitted multivariate linear-regression model and estimates for the various parameters of interest are obtained, the question about the contribution of the independent variables to the prediction of the dependent variable (*Y*) must be answered. One basic type of such a test to answer this question, according to Kleinbaum *et al*. (1988), can be written as: an *overall significance test*. Taken collectively, does the entire set of independent variables (or equivalently, the fitted model itself) contribute significantly to the prediction of the dependent variable *Y*?

To perform an overall significance test, use of the *MSR* and *MSE* from the ANOVA table are required. Null hypothesis for this test would be stated as H_0: "*all k independent variables considered together do not explain a significant amount of the variation in the dependent variable Y*." Calculate the F-statistic as F = *MSR*/*MSE*. Then, the computed value of F can be compared with the critical point $F_{k,n-k-1,1-\alpha}$, with α being the preselected significance level of 0.05. For example, the critical F point with $k = 3$ and $n = 183$ equals 2.66. The critical F point with $k = 3$ and $n = 59$ equals 2.76. The critical F point with $k = 2$ and $n = 53$ equals 3.17. Reject H_0 if the computed F-statistic exceeded the critical point, meaning that the k independent variables do explain a significant amount of the variation in the dependent variable *Y*.

The p-level determines statistical significance of the analysis, and represents a decreasing index of the reliability of a result. Higher p-levels, indicate a less likely occurrence that the observed relation between independent variables will be true. Additionally, p-level represents the probability of error involved in accepting the observed result as valid. Specifically, the p-level represents the probability of error associated with accepting an observed result as valid or representative of the population of observed results. For purposes of this analysis, a value of 0.05 (95% confident) or less for the p-level was treated as an acceptable error level.

4.5.2 Statistical Assumptions

Ensuing assumptions were obtained from Kleinbaum *et al*. (1988). The following assumptions are the typical assumptions for multivariate linear regression:

Assumption 1: *Existence*. For each specific combination of values of the independent variables, the dependent variable (Y) represents a random variable with a certain probability distribution having finite mean and variance.

Assumption 2: *Independence*. The Y observations are statistically independent of one another.

Assumption 3: *Linearity*. The mean value of the dependent variable (Y) for each specific combination of independent variables equals a linear function of the independent variables.

Assumption 4: *Homoscedasticity*. Constant variance of the dependent variable (Y) for any fixed combination of independent variables. Assumption 4 must be considered only when the data show very obvious and significant departures from homogeneity. In general, mild departures will not have too adverse an effect on the results.

Assumption 5: *Normality*. For any fixed combination of independent variables, the dependent variable (Y) follows a normally (Gaussian) distribution.

In order to assure that these assumptions are addressed, several tests are performed. A listing of the types of tests and brief descriptions from Kleinbaum *et al*. (1988) follows:

- *Plot of predicted values versus observed values* – Checks to determine which portions of the data do not fit particularly well with the rest of the data, suggesting another relationship and also shows how well the computed relationship matches the actual data.
- *Plot of predicted values versus the residual scores* – Checks to ensure that the relationship chosen can be considered linear in nature. If the relationship forms a

homogeneous distribution of points around the horizontal center line, the relationship can be considered linear. If any patterns are present in the plot, it may indicate the need for data transformation or that a multivariate linear regression may not be valid.

- *Normal probability plot of residuals* – Checks to ensure that all of the variables and their residuals are normally distributed (Gaussian). When the plotted data closely approximate the straight line, the variables and their residuals are considered normally distributed and assures that the data can be analyzed using multivariate linear regression.

4.6 Soil-loss Prediction Equation

Resulting from the rainfall parameter discussion in Section 2.5 and the variable selection analysis presented in Section 4.4, it was concluded that log (cumulative soil loss + 1) was a function of the independent variables presented in Eq. (4.8):

$$\log\,(\text{cumulative soil loss} + 1) = f\begin{pmatrix}\text{rainfall intensity, plot area, duration, slope gradient,} \\ \text{median raindrop size, raindrop kinetic energy,} \\ \text{percent clay, percent compacted}\end{pmatrix} \qquad \textbf{Eq. (4.8)}$$

Table 4.3 presents the data corresponding to each of the variables presented in Eq. (4.8) and utilized for analysis.

Table 4.3 – Data utilized for analysis

Log (cumulative soil loss + 1) (tons/acre)	**Rainfall intensity (in./hr)**	**Plot area (acre)**	**Duration (hrs)**	**Slope gradient (ft/ft)**	**Median raindrop size (mm)**	**Raindrop kinetic energy (ft-poundal *1,000)**	***% clay***	***% compacted***
1.1	1.9	0.0040	0.33	0.45	2.3	3.5	0.01	0.75
1.9	3.7	0.0040	0.67	0.45	2.3	3.5	0.01	0.75
2.4	6.3	0.0040	1.00	0.45	2.3	3.5	0.01	0.75
1.0	1.9	0.0040	0.33	0.33	2.3	3.5	0.01	0.75
1.9	3.7	0.0040	0.67	0.33	2.3	3.5	0.01	0.75

Log (cumulative soil loss + 1) (tons/acre)	Rainfall intensity (in./hr)	Plot area (acre)	Duration (hrs)	Slope gradient (ft/ft)	Median raindrop size (mm)	Raindrop kinetic energy (ft-poundal *1,000)	*% clay*	*% compacted*
2.4	6.3	0.0040	1.00	0.33	2.3	3.5	0.01	0.75
1.1	1.9	0.0040	0.33	0.25	2.3	3.5	0.01	0.75
1.8	3.7	0.0040	0.67	0.25	2.3	3.5	0.01	0.75
2.3	6.3	0.0040	1.00	0.25	2.3	3.5	0.01	0.75
0.9	2.0	0.0040	0.33	0.33	2.3	3.5	0.01	0.75
1.8	3.5	0.0040	0.67	0.33	2.3	3.5	0.01	0.75
2.2	6.3	0.0040	1.00	0.33	2.3	3.5	0.01	0.75
1.1	2.0	0.0040	0.33	0.33	2.3	3.5	0.01	0.75
1.9	3.5	0.0040	0.67	0.33	2.3	3.5	0.01	0.75
2.3	6.3	0.0040	1.00	0.33	2.3	3.5	0.01	0.75
0.1	2.3	0.0073	0.33	0.33	2.0	1.7	0.11	0.77
1.0	4.3	0.0073	0.67	0.33	2.0	1.7	0.11	0.77
1.4	5.5	0.0073	1.00	0.33	2.0	1.7	0.11	0.77
0.0	1.8	0.0073	0.33	0.33	2.0	1.7	0.11	0.77
0.8	2.9	0.0073	0.67	0.33	2.0	1.7	0.11	0.77
1.2	4.6	0.0073	1.00	0.33	2.0	1.7	0.11	0.77
0.0	2.4	0.0073	0.33	0.33	2.0	1.7	0.11	0.77
1.1	4.6	0.0073	0.67	0.33	2.0	1.7	0.11	0.77
1.4	6.3	0.0073	1.00	0.33	2.0	1.7	0.11	0.77
0.0	2.9	0.0073	0.33	0.33	2.0	1.7	0.11	0.77
1.0	5.3	0.0073	0.67	0.33	2.0	1.7	0.11	0.77
1.4	5.9	0.0073	1.00	0.33	2.0	1.7	0.11	0.77
0.4	2.0	0.0073	0.33	0.33	2.3	2.6	0.11	0.75
1.7	5.6	0.0073	0.67	0.33	2.3	2.6	0.11	0.75
2.1	7.4	0.0073	1.00	0.33	2.3	2.6	0.11	0.75
0.4	2.3	0.0073	0.33	0.33	2.3	2.6	0.11	0.75
1.6	4.4	0.0073	0.67	0.33	2.3	2.6	0.11	0.75
2.0	5.6	0.0073	1.00	0.33	2.3	2.6	0.11	0.75
0.6	2.1	0.0073	0.33	0.33	2.3	2.6	0.11	0.75
1.9	4.3	0.0073	0.67	0.33	2.3	2.6	0.11	0.75
2.1	5.4	0.0073	1.00	0.33	2.3	2.6	0.11	0.75
0.5	1.8	0.0073	0.33	0.33	2.3	2.6	0.11	0.75
1.7	4.9	0.0073	0.67	0.33	2.3	2.6	0.11	0.75
2.1	6.9	0.0073	1.00	0.33	2.3	2.6	0.11	0.75
0.3	1.7	0.0073	0.33	0.33	2.3	2.6	0.37	0.75
1.2	4.5	0.0073	0.67	0.33	2.3	2.6	0.37	0.75
1.7	6.5	0.0073	1.00	0.33	2.3	2.6	0.37	0.75
1.5	5.0	0.0018	0.50	0.40	4.0	21.2	0.12	0.72
2.0	5.0	0.0018	1.00	0.40	4.0	21.2	0.12	0.72
1.6	5.0	0.0018	0.50	0.40	4.0	21.2	0.12	0.72
2.0	5.0	0.0018	1.00	0.40	4.0	21.2	0.12	0.72
1.5	5.0	0.0018	0.50	0.40	4.0	21.2	0.12	0.72
2.3	5.0	0.0018	1.00	0.40	4.0	21.2	0.12	0.72
2.0	7.0	0.0018	0.50	0.40	4.0	21.2	0.12	0.72
2.5	7.0	0.0018	1.00	0.40	4.0	21.2	0.12	0.72
1.3	5.0	0.0018	0.50	0.40	4.0	21.2	0.12	0.88

Log (cumulative soil loss + 1) (tons/acre)	Rainfall intensity (in./hr)	Plot area (acre)	Duration (hrs)	Slope gradient (ft/ft)	Median raindrop size (mm)	Raindrop kinetic energy (ft-poundal *1,000)	*% clay*	*% compacted*
1.7	5.0	0.0018	1.00	0.40	4.0	21.2	0.12	0.88
1.2	5.0	0.0018	0.50	0.40	4.0	21.2	0.12	0.88
1.6	5.0	0.0018	1.00	0.40	4.0	21.2	0.12	0.88
1.4	5.0	0.0018	0.50	0.40	4.0	21.2	0.12	0.88
1.7	5.0	0.0018	1.00	0.40	4.0	21.2	0.12	0.88
1.3	3.5	0.0041	0.50	0.33	3.5	13.4	0.38	0.89
1.6	3.5	0.0041	1.00	0.33	3.5	13.4	0.38	0.89
1.8	3.5	0.0041	1.50	0.33	3.5	13.4	0.38	0.89
1.4	3.5	0.0041	0.50	0.50	3.5	13.4	0.38	0.89
1.6	3.5	0.0041	1.00	0.50	3.5	13.4	0.38	0.89
1.8	3.5	0.0041	1.50	0.50	3.5	13.4	0.38	0.89
2.1	3.5	0.0041	0.50	0.33	3.5	13.4	0.12	0.71
2.4	3.5	0.0041	1.00	0.33	3.5	13.4	0.12	0.71
2.6	3.5	0.0041	1.50	0.33	3.5	13.4	0.12	0.71
2.5	3.5	0.0041	0.50	0.50	3.5	13.4	0.12	0.71
2.8	3.5	0.0041	1.00	0.50	3.5	13.4	0.12	0.71
2.9	3.5	0.0041	1.50	0.50	3.5	13.4	0.12	0.71

Based on the linear fit for each of the independent variables plotted against the dependent variable shown in Figure 4.4, it was determined that a multivariate linear relationship was valid for describing the data. Figure 4.4 shows that each of the independent variables can be considered a linear function of the dependent variable and since each of the slopes of the individual regression lines were approximately equal, a multivariate linear relationship was considered valid to pursue (Graybill and Iyer, 1994).

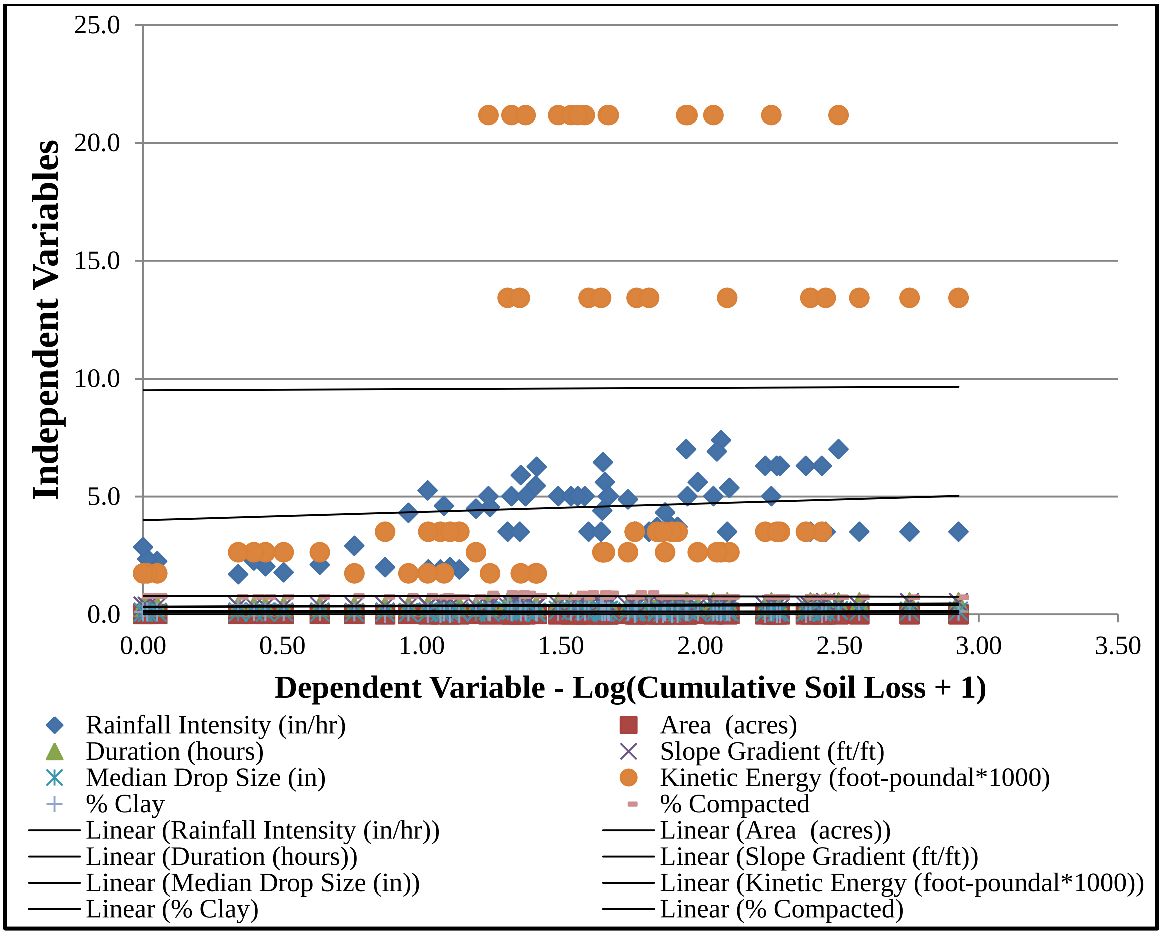

Figure 4.4 – Plot of raw data for log (cumulative soil loss + 1) data

From the statistical analysis presented in Section 4.5 and the software program Statistica (StatSoft®, 2011), the soil-loss prediction equation follows as:

$$\begin{aligned}\log_{10}(CSL+1) &= -5.040+0.309(I)-174.607(A)+7.722(D)+0.816(S)\\ &+72.307(RD_{50})-0.379(KE)-1.596(\%\ clay)-2.411(\%\ compacted)\end{aligned} \qquad \textbf{Eq. (4.9)}$$

where

CSL	=	cumulative soil loss (tons/acre);
I	=	rainfall intensity (in./hr);
A	=	area of the plot size (acres);
D	=	duration of the event (hrs);

S	=	slope gradient of the plot (ft/ft);
RD_{50}	=	median raindrop size (in.);
KE	=	kinetic energy of the median raindrop size (ft-poundal*1,000);
% clay	=	percentage of clay contained within soil (decimal %); and
% compacted	=	compaction percentage of the surface soil (decimal %).

During the statistical analysis, sixty-eight data points were utilized with no outliers. Table 4.4 presents the multivariate linear-regression summary associated with Eq. (4.9). Table 4.5 displays an ANOVA table corresponding to Eq. (4.9).

Table 4.4 – Multivariate linear-regression summary statistics corresponding to Eq. (4.9)

Number of measurements: 68
Dependent variable: log (cumulative soil loss + 1)

Independent variables	Standardized regression coefficient β	Standard error of β	Regression coefficient B	Standard error of B	t-statistic(20)	p-level
intercept			-5.040	0.95418	-5.2824	0.000002
rainfall intensity	0.68931	0.046193	0.309	0.02071	14.9223	0.000000
plot area	-0.55155	0.101065	-174.607	31.99495	-5.4573	0.000001
duration	0.91436	0.219804	7.722	1.85618	4.1599	0.000105
slope gradient	0.06971	0.053360	0.816	0.62460	1.3064	0.196485
median raindrop size	3.24026	0.460333	72.307	10.27240	7.0389	0.000000
raindrop kinetic energy	-4.24570	*0.355587*	-0.379	0.03178	-11.9400	0.000000
percent clay	-0.25029	0.072474	-1.596	0.46209	-3.4535	0.001030
percent compacted	-0.19842	0.054178	-2.411	0.65821	-3.6625	0.000536
correlation coefficient, R =	0.945					
coefficient of determination, R^2 =	0.893					
adjusted R^2 =	0.879					
F-statistic =	61.78					
p <	0.000					
standard error of estimate	0.240					

Table 4.5 – ANOVA table associated with Eq. (4.9)

Source	Degrees-of-freedom (*df*)	Sum of squares (*SS*)	Mean square (*MS*)	F-statistic	p-level
regression	8	28.42	3.55	61.78	0.00
residual	59	3.39	0.57		
total		31.81			

Listed in Table 4.4, the adjusted R^2 from the analysis for Eq. (4.9) was 0.88 (rounded up from 0.879), indicating that 88% of the variability in the data was explained by the relationship. An overall significance test indicated that the critical F value for k = 8 and n = 59 was 2.10. Since the F-statistic reported in Table 4.5 of 61.78 was greater than 2.10, the eight independent variables explained a significant amount of the variation in the dependent variable log (cumulative soil loss + 1). Additionally, the p-level of all independent variables except slope gradient and the overall p-level were all less than or equal to the selected value of 0.05, therefore, the analysis was determined to be statistically significant. Slope gradient was left in the analysis due to the physical importance of this parameter to the erosion process, even though the p-value for the regression analysis was higher than 0.05.

Figure 4.5 presents a plot of observed values versus predicted values for the log data. Figure 4.5 indicates that Eq. (4.9) can be considered a reliable prediction equation, having points both above and below the line of equal prediction, with a variability in predicted values of plus or minus 20% for an observed value.

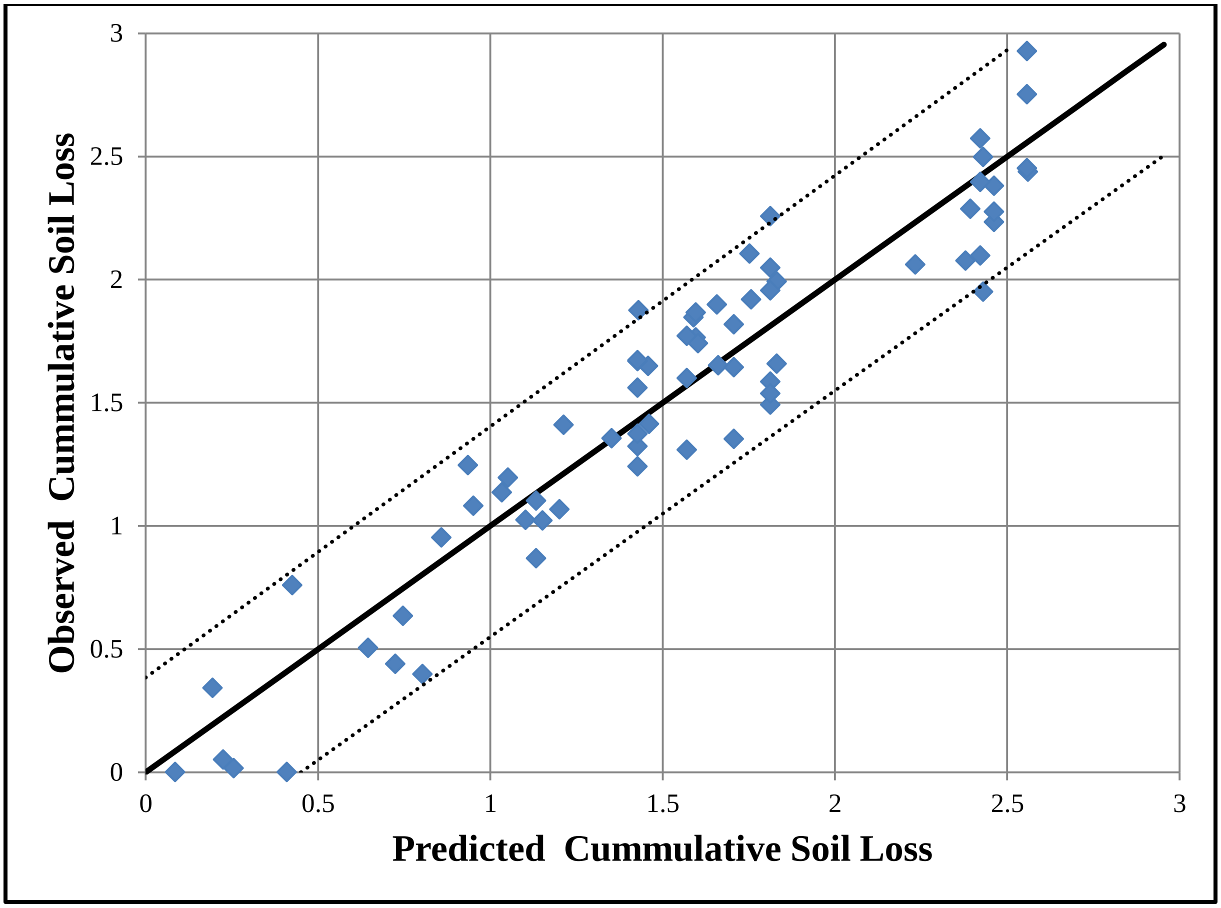

Figure 4.5 – Observed versus predicted values for Eq. (4.9)

Figure 4.6 displays a plot of predicted values versus the residual scores for the dependent variable. Data points plotted in Figure 4.6 form a homogeneous distribution of points around the horizontal centerline verifying that the relationship was linear.

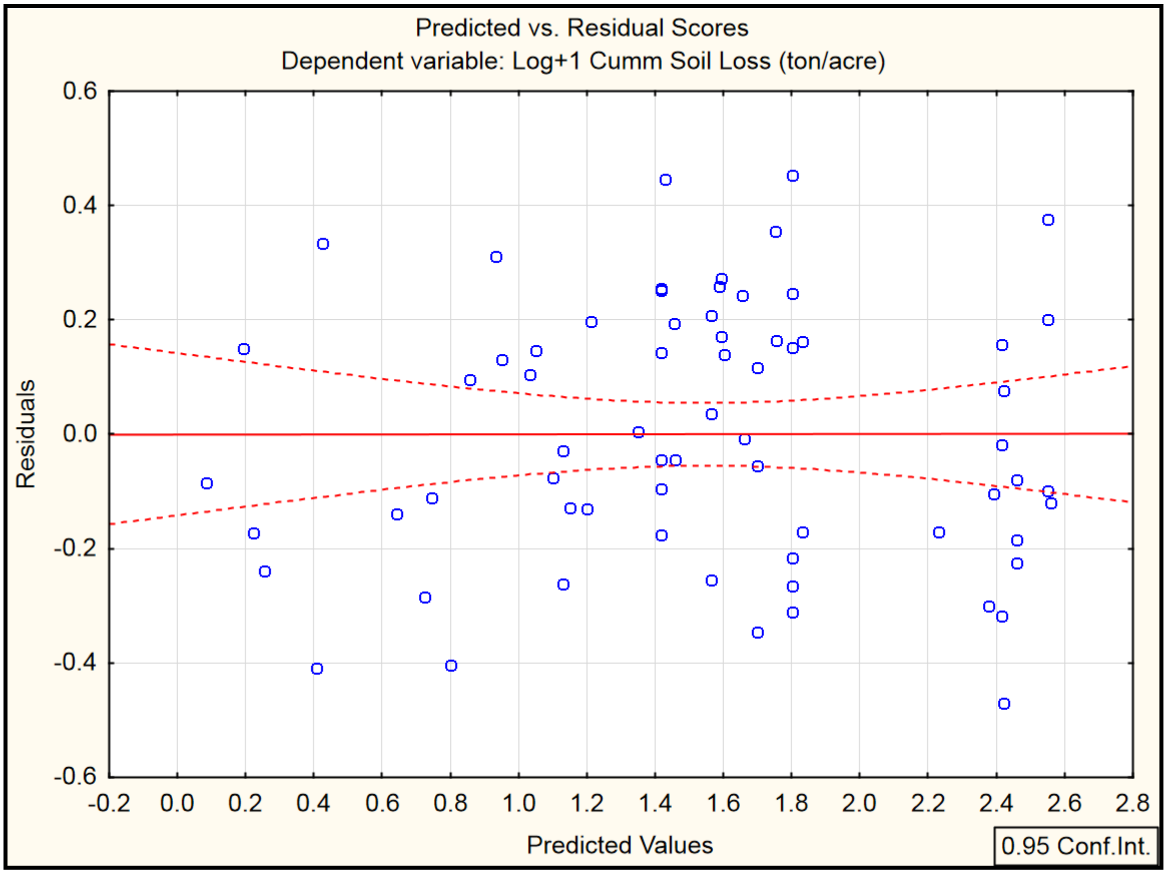

Figure 4.6 – Predicted values versus residual scores for Eq. (4.9)

Figure 4.7 presents the normal probability plot of residuals for the data. Figure 4.7 indicates that the residuals very closely approximated a normal distribution since the plotted points follow the straight line, assuring that the data could be analyzed using multivariate linear regression.

Data collected were developed into independent variables that were used in a multivariate linear-regression analysis to develop Eq. (4.9). Eq. (4.9) had a R^2 of 0.88, indicating that 88% of the variability in the data was explained by the relationship. Additionally, the data satisfied the overall significance test and the individual tests for checking multivariate linear-regression validity.

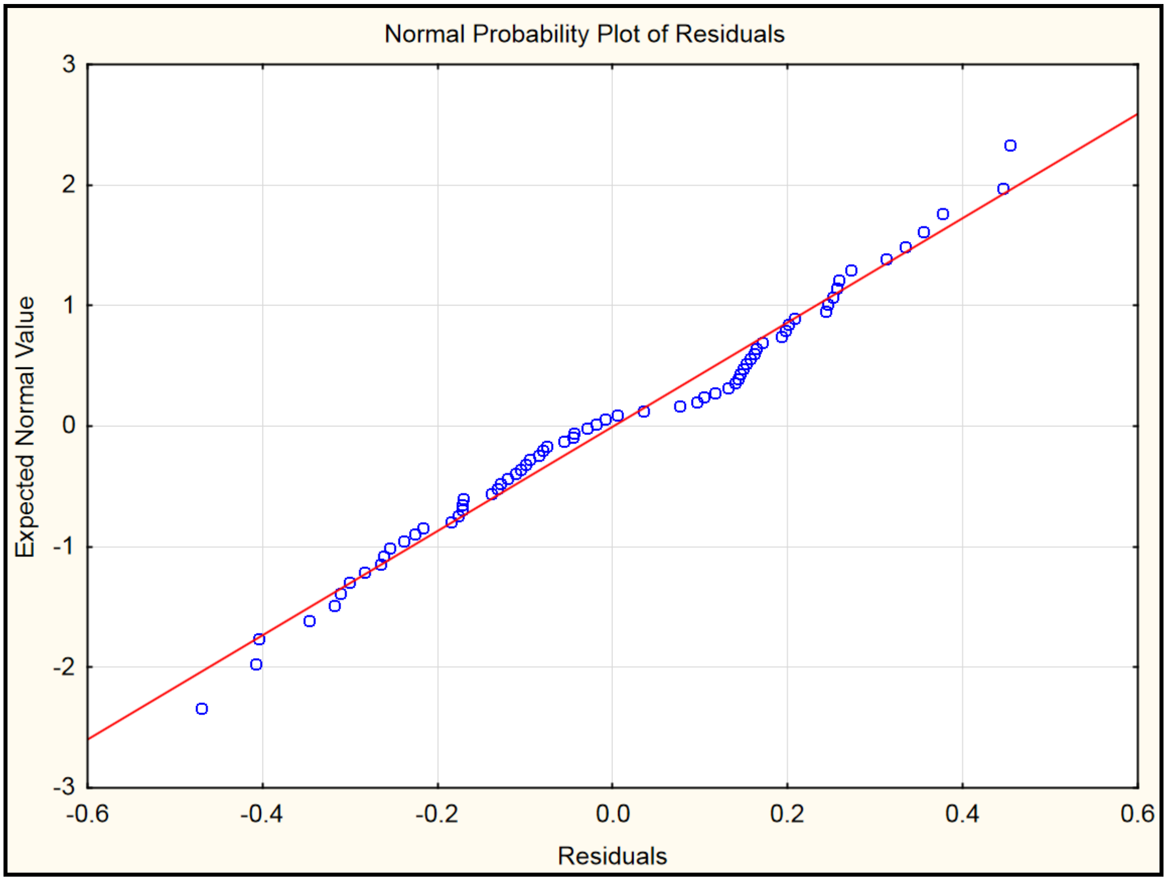

Figure 4.7 – Normal probability plot of residuals for Eq. (4.9)

5 RESULTS

5.1 Introduction

Now that a predictive equation has been developed via Eq. (4.9) which is presented again, without the log transformation, as Eq. (5.1); it makes sense to compare and discuss differences to the standard of practice (RUSLE), and to discuss boundary conditions and equation applicability. Eqs. (4.9) and (5.1) have a variability in predicted values of plus or minus approximately 20%:

$$CSL = 10^{\left(\begin{array}{l}-5.040+0.309(I)-174.607(A)+7.722(D)+0.816(S)+72.307\\(RD_{50})-0.379(KE)-1.596(\%\ clay)-2.411(\%\ compacted)\end{array}\right)} - 1 \qquad \textbf{Eq. (5.1)}$$

5.2 Comparison to the RUSLE

Eq. (4.9) was compared to the RUSLE. Figure 5.1 presents the predicted versus observed plot for Eq. (4.9) and the RUSLE using a log transformation to compare the same data as originally presented.

Figure 5.1 presents the data in graphic form of observed cumulative soil loss versus predicted cumulative soil loss for both the RUSLE and Eq. (4.9). As can be observed in Figure 5.1, Eq. (4.9) more-accurately predicts the observed bare-soil loss across multiple laboratories than the RUSLE, significantly tightening up the data around the line of equal fit. As an example, the absolute average predicted variance for any observed value with Eq. (4.9) is about 20% or less, whereas the absolute average predicted variance for any observed value with the RUSLE is about 65%. On average, Eq. (4.9), when applied to the bare-soil data sets from all of the various laboratories, does not overpredict or underpredict, with an equation that has an R^2 of 0.88, explaining 88% of the variability in the data. In stark contrast, the RUSLE that is the standard of practice for field application of large-scale laboratory testing for ASTM D6459 does not adequately predict the observed bare-soil loss across multiple laboratories, as the data are too scattered to indicate a consistent trend with an R^2 of only about 0.14, explaining only 14% of the variability in the data. As can be seen in Figure 5.1, for the observed value of 1, the RUSLE predicted value was anywhere from 0.5 to 2.0, which is a maximum error as much as 100%. Whereas, for the observed value of 1, Eq. (4.9) predicted value was from 0.86 to 1.2, which is a maximum error of 20%. A summary table of the comparison between Eq. (4.9) and RUSLE is provided in Table 5.1.

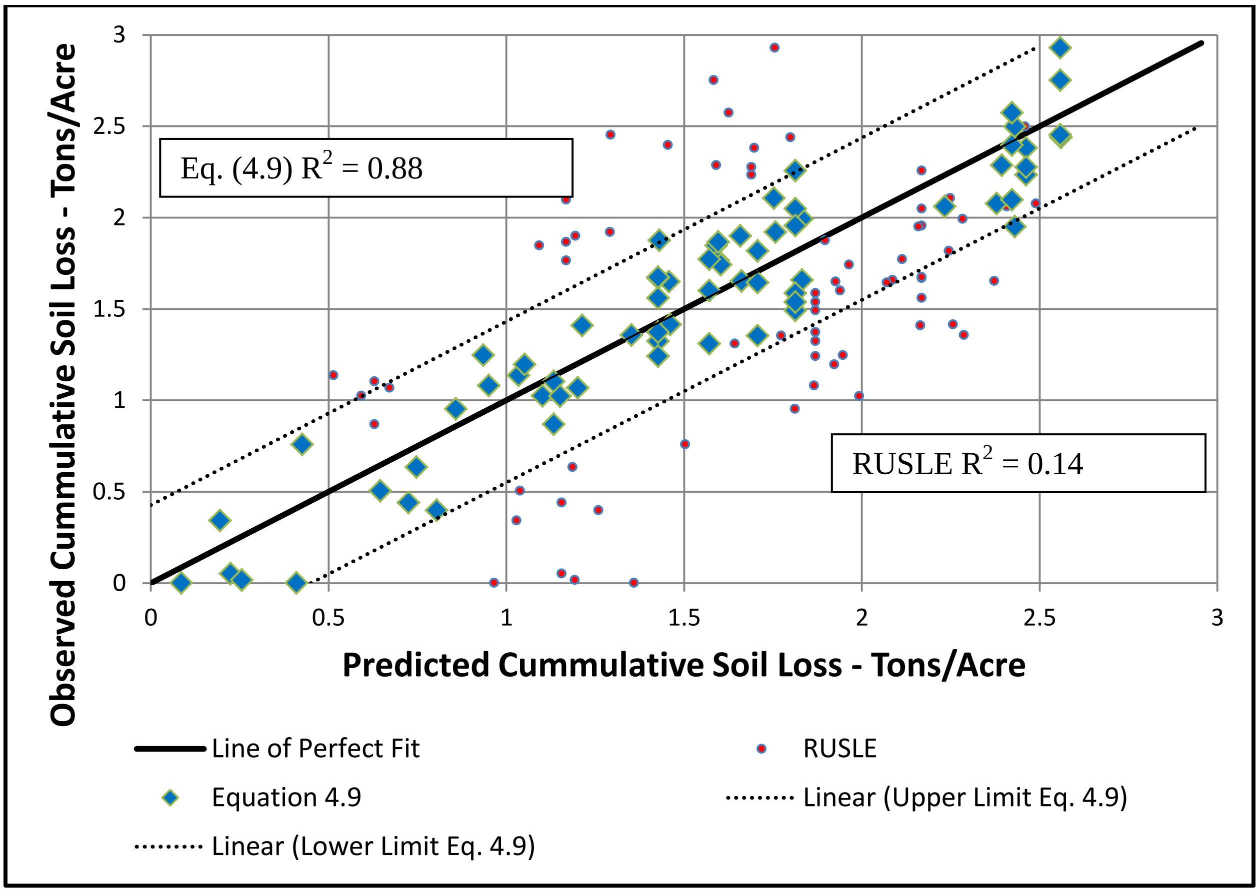

Figure 5.1 – Predicted versus observed comparison

Table 5.1 – RUSLE Compared to Eq. (4.9) Based on Figure 5.1

Comparison Parameter	RUSLE	Eq. (4.9)
R^2	0.14	0.88
Absolute Average Predicted Variance for an Observed Value	65 %	20 %
Error associated with Observed value of 1.00	100 %	20 %

For further comparison, plots of how each individual laboratory contributed to Eq. (4.9) and for RUSLE are presented in Figures 5.2 and 5.3, respectively. As can be observed in Figures 5.2 and 5.3, Eq. (4.9) collapses all of the individual laboratory variability around the line of equal fit and instead of laboratory deviations from the line of equal fit of 16 to 70% with Figure 5.3, Eq. (4.9) takes the deviation from the line of equal fit to a range of 0 to 4%.

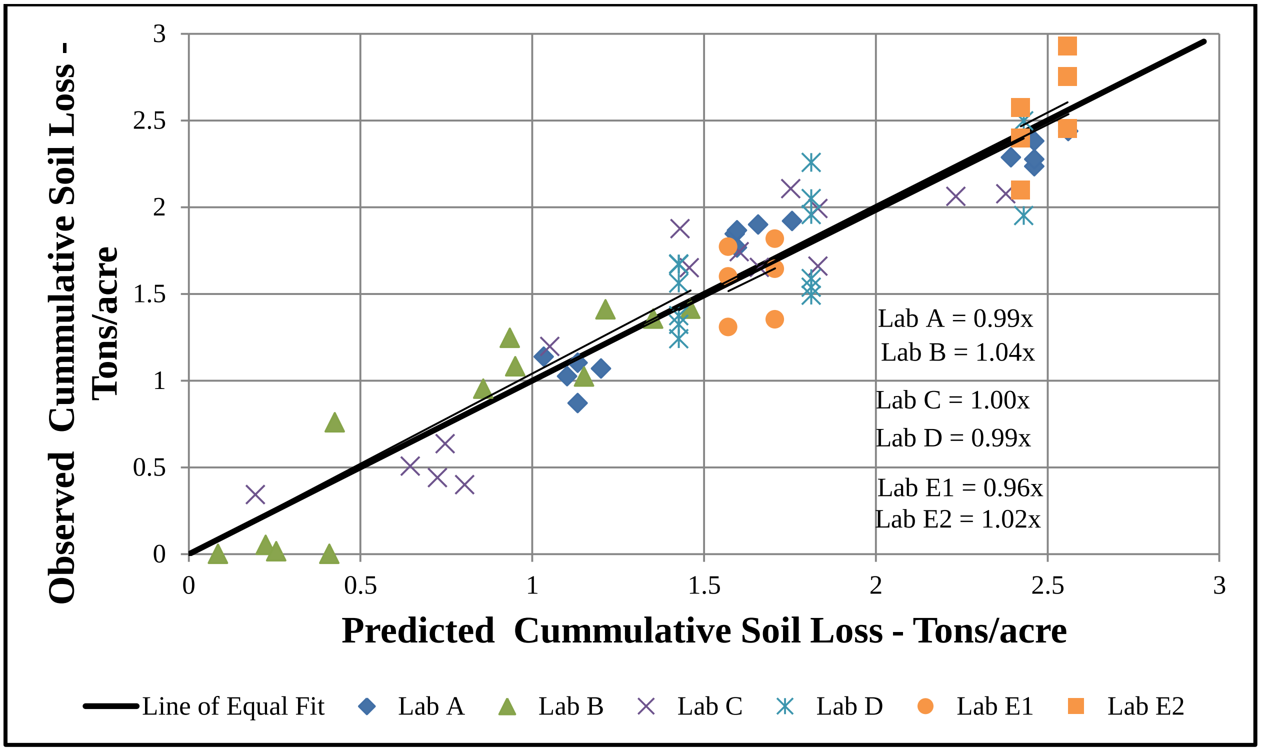

Figure 5.2 – Predicted versus observed laboratory comparison for Eq. (4.9)

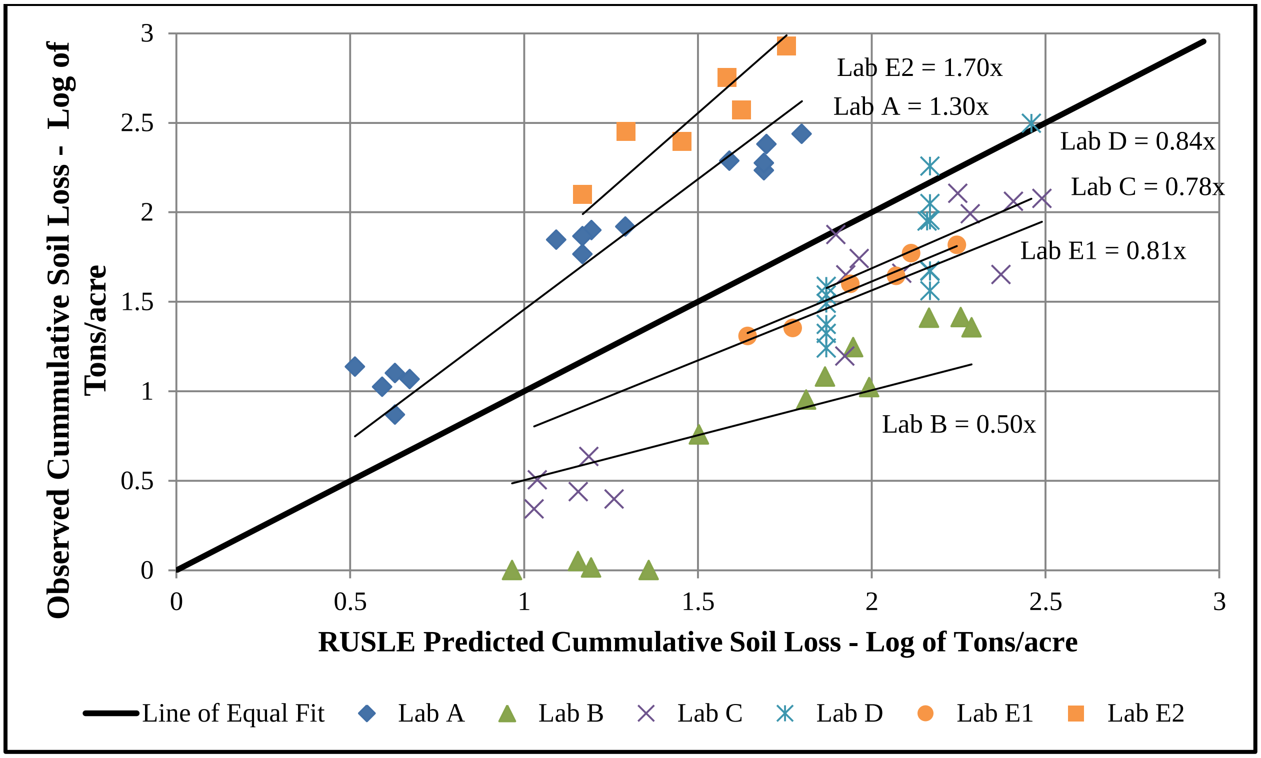

Figure 5.3 – Predicted versus observed laboratory comparison for RUSLE

The current standard of practice using the RUSLE and applying it at large-scale laboratories, and then using the cover factor value to apply results to the field has been leading to significant errors in soil-loss related calculations that are used by practicing engineers to specify erosion-control products. Depending on the conditions that are tested at each laboratory, the RUSLE would lead practicing engineers to believe that as much as 1.4 tons/acre of soil loss would occur when the actual value was zero. On the other extreme, the RUSLE predicts 1.3 tons/acre when the actual value was 2.5 tons/acre. The variability that the RUSLE allows in overprediction and underprediction has been misleading practicing engineers. Eq. (4.9) does a much better job of distributing the variability around the line of equal fit and reducing overall variability, which will lead practicing engineers to more consistent and reliable soil-loss calculations that are based on large-scale laboratory testing. Some of the reasons that the RUSLE may not accurately predict soil loss in a large-scale laboratory setting are:

- the RUSLE was not developed to be used on individual storm events, but is being misapplied for individual events to determine cover factors;
- the RUSLE does not adequately account for the effects of kinetic energy of raindrops; and
- the RUSLE does not adequately account for the effects of soil compaction and the interaction of clay particles.

Eq. (4.9) accounts for the above-listed deficiencies of the RUSLE as well as accounting for other key physical processes that occur during soil loss. Therefore, Eq. (4.9) should replace the RUSLE as the standard of practice for large-scale laboratory soil-loss calculations that subsequently get applied to the field.

5.3 Boundary Conditions

During the development of any predictive relationship performed in controlled laboratory settings, the boundary conditions or limitations imposed during testing should be considered when attempting to apply the relationship outside of the laboratory. The developed predictive relationship for this study should be applied within the bounds of the following ranges of testing parameters:

- rainfall intensity: 1.7 to 7.4 in./hr;
- plot area: 0.0018 to 0.0073 acres (78 to 320 ft^2);
- slope gradient: 0.25 to 0.50 ft/ft (4H:1V to 2H:1V, Horizontal:Vertical);
- median raindrop size: 2.0 to 4.0 mm;
- duration of event: 0.5 to 1.5 hrs;
- raindrop kinetic energy (times 1,000): 1.7 to 21.2 ft-poundal*1,000;

- clay percentage in soil: 0.01 to 0.38 (1 to 38%); and
- soil compaction percentage: 0.71 to 0.89 (71 to 89%).

The above conditions represent a wide range of conditions that can typically be found at a construction site where erosion-control products are often used. The above conditions do not emcompass all of the possible conditions that could be encountered at a construction site, but as indicated, do provide a decent range of conditions which currently are being applied to construction sites.

5.4 Equation Applicability

During examination of Eq. (4.9), it was determined that the area term was negatively proportional to resulting soil-loss values. From a purely physical analysis of terms, as area increases, so should soil loss, meaning that the area term should be positively proportional to the resulting soil loss. Within the bounds of the data developed and applied to the ranges of the laboratories, Eq. (4.9) predicts values as outlined, however, applicability of Eq. (4.9) outside of the boundary conditions of the areas provided by each laboratory will likely lead to prediction issues. The area term was left as negatively proportional to the soil loss in order to demonstrate that when a more appropriate set of parameters was selected to determine soil loss, a much better prediction equation would be possible. In order to correct the sign of the area term, additional data with much larger areas would be needed.

6 CONCLUSIONS, EXAMPLE CALCULATION, AND RECOMMENDATIONS

Based on research presented in this dissertation, a better understanding of the processes at work during large-scale rainfall erosion has been presented and a prediction equation for soil loss that unifies the large-scale testing laboratory data now exists for the erosion-control community. This new equation should be utilized by practicing engineers using large-scale testing facilites to predict erosion that can be applied to field applications. Data from five different laboratory setups were examined and included in the developed predictive relationship. A summary of the conclusions from this dissertation follows:

- The existing and most-commonly used prediction equation (RUSLE) that is currently employed for large-scale laboratory analysis and subsequent field application is inadequate as summarized below in Table 6.1 and further explained in Section 5.2.

Table 6.1 – RUSLE Compared to Eq. (4.9) Based on Figures 5.1, 5.2, and 5.3

Comparison Parameter	RUSLE	Eq. (4.9)
R^2	0.14	0.88
Absolute Average Predicted Variance for an Observed Value	65%	20%
Error associated with Observed value of 1.00	100%	20%
Range of Laboratory Deviation from line of Equal Fit	16 – 70%	0 – 4%

- A large-scale rainfall soil-loss prediction equation was developed and determined to be a function of the following key parameters, in order of significance:
    - raindrop kinetic energy (*KE*);
    - median raindrop size (RD_{50});
    - duration (*D*);
    - rainfall intensity (*I*);

- plot area (A);
- percentage of clay in the soil (*% clay*);
- compacted soil percentage (*% compacted*); and
- slope gradient (S).

- Eq. (4.9), for prediction of rainfall-induced soil loss, developed from sixty-eight data points collected for this study, was presented. Eq. (4.9) had a R^2 of 0.88 and is presented below:

$$\log_{10}(CSL+1) = -5.040 + 0.309(I) - 174.607(A) + 7.722(D) + 0.816(S) + 72.307(RD_{50}) - 0.379(KE) - 1.596(\%\ clay) - 2.411(\%\ compacted)$$

A more practical version of Eq. (4.9) for field application was presented as Eq. (5.1):

$$CSL = 10^{\left(\begin{array}{l} -5.040+0.309(I)-174.607(A)+7.722(D)+0.816(S)+72.307 \\ (RD_{50})-0.379(KE)-1.596(\%\ clay)-2.411(\%\ compacted) \end{array}\right)} - 1 \qquad \textbf{Eq. (5.1)}$$

- The new prediction equation accounts for several deficiencies of the RUSLE including the use as an event-based equation, kinetic energy, and soil compaction.

6.1 Example Calculation

In order to demonstrate how Eq. (5.1) (Eq. (4.9) without a log transformation) would be used at a construction site, an example will be provided with the following conditions:

- Construction site located in Little Rock, Arkansas, with a reported rainfall factor of about 350, which corresponds well to Figure 2.4.
- The construction site slope of interest has a length of 25 ft and a width of 10 ft with a slope gradient of 3H:1V.

- The slope was constructed with fill material consisting of a sandy clay loam as classified by the USDA textural soil triangle and compacted to 85% of standard proctor. If a compaction percentage was not provided, on-site testing with a nuclear density gage along with a soil analyis can be used to determine soil compaction. The USDA soil textural triangle, as presented in Figure 6.1, can be used to determine soil percentages. The percentage of clay is estimated to be 38%, the percentage of silt to be 16%, and the percentage of sand to be 44% for the clay loam in this example.

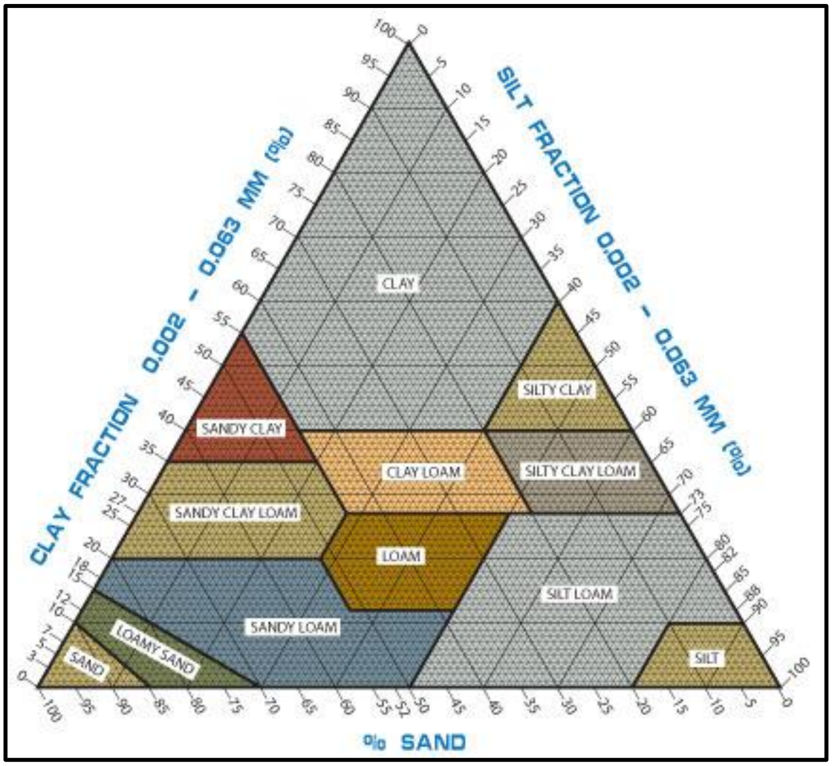

Figure 6.1 – USDA soil textural triangle

- The design storm that was selected is the 50-yr, 30-min event, which corresponds to a rainfall intensity of about 2.6 in./hr. This information can be found at: http://dipper.nws.noaa.gov/hdsc/pfds/. Select the state of interest and then download the appropriate document for the selected design storm.

- In order to perform a calculation using Eq. (5.1), the following pieces of information are needed:
    - *Rainfall intensity* – obtained from the design storm and the National Oceanic and Atmospheric Administration (NOAA) = 2.6 in./hr.
    - *Plot area* – obtained from measuring the plot of interest = 0.0057 acres (25 ft x 10 ft converted to acres).
    - *Duration* – obtained from the design storm that was selected = 0.5 hrs.
    - *Slope* – surveyed on site = 0.333 ft/ft.
    - *Percentage of clay* – determined from soil analysis or textural triangle = 0.30.
    - *Percentage of surface compaction* – determined from nuclear density gage and soil analysis = 0.85.
    - *Median raindrop diameter* – determined from the Laws and Parson curve on Figure 2.3 = 2.6 mm = 0.1024 in. (from 2.6 in./hr rainfall intensity).
    - *Raindrop kinetic energy* – determined from Eq. (2.1) times 1,000, and the following supplemental equations and Figure 6.2 for determining velocity of a raindrop:
        - Mass of raindrop = density of water * volume of the raindrop (assume a sphere for calculations);
        - Density of water = 62.4 lbs/ft^3 = 0.0361 lb/in.^{3};
        - Volume of a sphere with a diameter of 0.1024 in. = 4/3 * Pi * radius^3 = 0.0006 in.^{3}; and
        - Mass of drop = 0.0361 * 0.0006 = 0.0000202 lb.

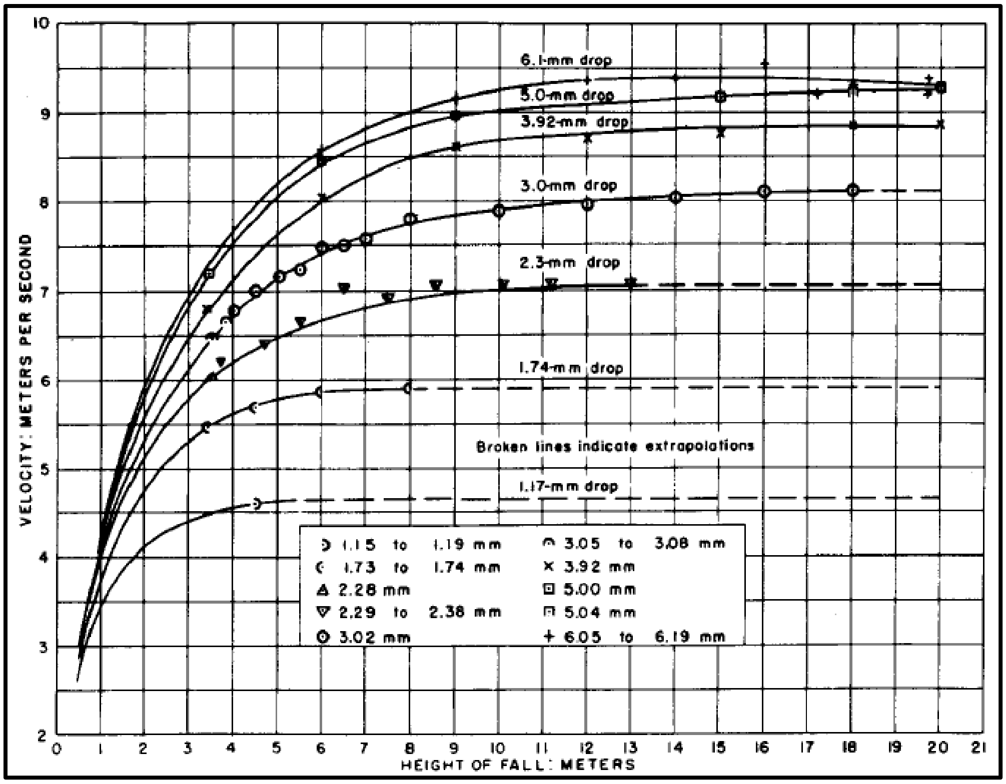

Figure 6.2 – Velocity-fall Height-median Raindrop Curves (Laws, 1941)

- Velocity of raindrop – use Figure 6.2 with a fall height of 20 m (natural rainfall), a raindrop size of 2.6 mm = about 7.5 m/s = 24.6 ft/s.
- Kinetic energy of the median raindrop from Eq. (2.1) = 0.5 * 0.0000202 * $(24.6)^2$ = 0.0061 * 1,000 = 6.1 ft-poundal*1,000.
- Plugging all of the known values into Eq. (5.1), yields: 22 tons/acre.
- Using the RUSLE with R = 350, K = 0.25 (from a soil type provided by one of the laboratories), L and S calculated from Section 2.4.4, and C and P equal to 1, yields: 64 tons/acre.
- RUSLE predicts a soil loss that is 2.9 times higher than Eq. (5.1).

6.2 Recommendations for Further Research

- Research presented herein was based on data collected from large-scale laboratories. Field data used to expand and confirm Eq. (4.9) would be critical for verifying the predictive relationship.
- The database consisted of bare-soil testing conditions and it would be logical to develop a prediction equation that accounts for the application of an erosion-control product.
- Allowing for more variation in the key prediction parameters would allow the equation to be more broadly applied.
- There is a need to develop a correlation between Eq. (4.9) and the RUSLE so that practitioners currently using the RUSLE have the ability to integrate their previous work.

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LIST OF ABBREVIATIONS

ASTM	American Society for Testing and Materials
ANOVA	analysis of variance
BMPs	best management practices
C&D	construction and development
CGP	Construction General Permit
ELGs	Effluent Limitations Guidelines
FHWA	Federal Highway Administration
H:V	Horizontal:Vertical
Lab	Laboratory
LLC	Limited Liability Company
NOAA	National Oceanic and Atmospheric Administration
NOI	Notice of Intent
NPDES	National Pollutant Discharge Elimination System
RUSLE	Revised Universal Soil Loss Equation
®	registered
SCS	Soil Conservation Service
SWPPP	Stormwater Pollution Prevention Plan
TRI	Texas Research International
TTI	Texas Transportation Institute
U. S.	United States
USDA	United States Department of Agriculture
USEPA	United States Environmental Protection Agency
USLE	Universal Soil Loss Equation