A rainfall simulator study of soil erodibility in the Gallatin National Forest, southwest Montana

by Ginger Lee Schmid

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Soils
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Abstract:
Adequate equations are a necessity for quantitatively predicting soil losses from precipitation events on nonagricultural soils in the Rocky Mountain west. A modified Meeuwig rainfall simulator was used to study sediment yield environments on wildland soils in the Gallatin National Forest of southwest Montana.

Sediment was collected from simulator plots under three different treatments: (1) natural ground cover intact, (2) vegetation and litter removed, and (3) soil surface removed to a depth of 15 cm. Sediment yields from these three treatments on fine textured soils formed on Cretaceous shales were compared to those from coarse textured soils formed on Pre-Cambrian metamorphics. Slope angle; percent of ground area covered by vegetation, litter and rock; and the soil properties of texture, bulk density, organic matter content and water content were measured as possible variables affecting erodibility. These soil and site characteristics were also used to determine if sediment yield prediction equations developed from Meeuwig's (1970,1971) simulator research on high elevation rangeland in the Intermountain west were applicable on forested lands in southwestern Montana.

Soil texture, soil water content, and percent of the soil surface protected by vegetation, litter, and rock were significantly different between soil textures and treatments. No significant differences were found between the fine and coarse textured sediment yields for any one treatment. Significant differences were seen between plot treatments when both textures were considered together. The sediment prediction equations developed by Meeuwig (1970,1971) did not accurately predict the sediment yields collected from this simulator study.

Lack of a significant difference in sediment yields from the two soil texture extremes was probably due to aggregation of clay in the shale soils to form sand sized particles. Significant differences in sediment yield between plot treatments support evidence that disturbance of a soil increases its erodibility. The failure of the Meeuwig equations to predict sediment yields on this study's sites in the Gallatin National Forest does not discredit Meeuwig's work, but rather emphasizes the natural variability involved in mountain soil environments, and the difficulties involved in quantifying soil erodibility in these areas.

A RAINFALL SIMULATOR STUDY OF SOIL ERODIBILITY IN THE GALLATIN NATIONAL FOREST, SOUTHWEST MONTANA

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APPROVAL

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This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citations, bibliographic style, and consistency, and is ready for submission to the College of Graduate Studies.

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ABSTRACT

Adequate equations are a necessity for quantitatively predicting soil losses from precipitation events on nonagricultural soils in the Rocky Mountain west. A modified Meeuwig rainfall simulator was used to study sediment yield environments on wildland soils in the Gallatin National Forest of southwest Montana.

Sediment was collected from simulator plots under three different treatments: (1) natural ground cover intact, (2) vegetation and litter removed, and (3) soil surface removed to a depth of 15 cm. Sediment yields from these three treatments on fine textured soils formed on Cretaceous shales were compared to those from coarse textured soils formed on Pre-Cambrian metamorphics. Slope angle; percent of ground area covered by vegetation, litter and rock; and the soil properties of texture, bulk density, organic matter content and water content were measured as possible variables affecting erodibility. These soil and site characteristics were also used to determine if sediment yield prediction equations developed from Meeuwig's (1970,1971) simulator research on high elevation rangeland in the Intermountain west were applicable on forested lands in southwestern Montana.

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INTRODUCTION

Erodibility is defined as a soil's susceptibility to erosion. A soil that is highly erodible is highly susceptible to erosion. There are inherent soil characteristics that have been shown to influence a soil's vulnerability to water erosion under certain conditions. These include particle size distribution, aggregation, bulk density, organic matter content and water content (Middleton, 1930; Bryan, 1968; Wischmeier and Mannering, 1969; Hudson, 1981).

The erodibility of agricultural soils in the central and eastern United States has been intensely studied over the past two decades (e.g. Olson and Wischmeier, 1963; Wischmeier and Mannering, 1969; Wischmeier, Johnson, and Cross, 1971; Wischmeier and Smith, 1978; Meyer, 1984). These studies have resulted in the development and use of the Universal Soil Loss Equation (USLE) to predict long term sediment loss due to erosion by rainfall (Wischmeier and Smith, 1978). A K factor for soil erodibility is included in the USLE, and it can be used to quantify the erodibility of soils formed under pedogenic environments similar to those used in the development of the USLE.

Pedogenic environments in the intermountain West are different from those studied in the development of the USLE. As the five factors governing soil formation change, so do the soil characteristics affecting erodibility and the role they play in water erosion environments. When topography and climate change, biological activity changes and the soil characteristics that control soil erodibility do not play the same roles as corresponding characteristics do in soils east of the Rocky Mountains. The USLE's K factor does not adequately represent soil erodibility in these western environments (Trieste and Gifford, 1980; Trott and Singer, 1983).

Erodibility Studies in the Intermountain West

A considerable amount of work has been done in the western United States on erodibility and related factors of soil erosion by water. Laboratory work in California (André and Anderson, 1961) resulted in a prediction equation that could be used for determining the relative erodibility of a watershed. This equation related a surface-aggregation and a dispersion ratio to parent material type, vegetation type, geographic zone and elevation.

A twenty year, multi-agency field project started in Colorado in 1953 (Schumm and Lusby, 1963) looked at the erosional and hydrological characteristics of grazed and ungrazed areas in small drainage basins developed on shale parent material. Results from the precipitation, runoff, and sediment yield portion of this project gave strong evidence of seasonal changes in the soil characteristics influencing erosion.

Rainfall simulations conducted under winter conditions in the Sierra Nevada Mountains northwest of Reno, Nevada (Haupt, 1967) resulted in restricted field conditions that did not allow a reliable statistical analysis. Qualitative conclusions indicated that litter and snow cover dissipated raindrop energy and increased infiltration, while exposed rock accelerated overland flow and erosion.

Rainfall simulator studies conducted on high elevation rangeland in Idaho, Montana and Utah (Meeuwig, 1970, 1971a) resulted in regression equations and related nomographs to predict sediment losses in certain erosion environments. These environments were identified by elevation, parent material, soil texture and vegetation type. The equations utilized percent ground cover, slope gradient, soil texture and soil organic matter content in predicting sediment losses. The percent of ground cover intercepting precipitation was the single most important factor in all erosion environments studied, but the magnitude of its role was highly dependent upon the slope gradient.

Meeuwig also conducted rainfall simulator studies in the Carson Range of the Sierra Nevada Mountains (1971b) where he was looking at the effect of location (depth in soil) and continuity of hydrophobic layers on infiltration. These rainfall simulations were conducted on several types of vegetation as well as on bare ground. The most severe hydrophobia and runoff was observed under Western white pine.

The importance of disturbance of the soil surface was investigated on pinyon-juniper sites in southern Utah (Gifford, 1973). Sites that were chained and then seeded to crested wheatgrass had higher runoff and sediment yields under natural precipitation events than the woodland control sites, even when ground cover on the grass sites increased to 74 percent coverage.

United States Forest Service concerns with the impacts of logging activities on the coarse textured soils of the Idaho Batholith initiated a six year study in the Payette National Forest (Megahan, 1975). Sediment production per unit area of the watershed was 150 times greater after construction of logging roads than it was in undisturbed areas. Eighty-four percent of the sediment from surface erosion measured during the period of study was produced in the first year after construction.

Seasonal variation of soil characteristics was observed in an infiltration study on pinyon-juniper sites in southeastern Utah (Gifford, 1979). Infiltration readings from simulated rainfall on uniform soils exhibited a wide range between minimum and maximum rates. Maximum infiltration occurred in early spring and the minimum rates were observed in late summer. Another rainfall simulator field study (Gifford, 1982) of infiltration in a Big sagebrush community in southern Idaho found that grazing eliminated seasonal variations in infiltration rates. This study also found that plots that had reduced infiltration due to grazing impacts took six years to recover once the animals were removed.

A laboratory study (Dadkhah and Gifford, 1980) evaluated ground cover and trampling rates without the seasonal soil influences. Indoor plot studies under simulated rainfall showed no significant increases in sediment yield once vegetation covered over 50 percent of the plot area. Increased trampling rates yielded uniform decreases in infiltration up to a 40 percent trampling level of animal impact, after which no significant changes in infiltration were observed.

Over 2000 plot years of data from 189 rainfall simulator field plots on rangeland in three western states and Australia were used to evaluate the use of the USLE on various rangeland conditions (Trieste and Gifford, 1980). USLE predictions did not match sediment yields collected from a majority of the field plots. The failure of the USLE to predict sediment yields under those rangeland circumstances represented by the 189 plots suggested the application of the equation in erosion environments dominated by single storm events to be unreliable. Another rangeland application of the USLE (Johnson, Savabi, and Loomis, 1984) was conducted on rainfall simulator plots in Idaho and Nevada. Predicted yields for tilled field plots were close to measured yields. Predicted yields were considerably higher than yields measured from nontilled-ungrazed plots, while predictions for nontilled-clipped plots were much lower than actual sediment yields.

A field study (Hart and Loomis, 1982) of sediment yields from snowmelt was conducted in the Wasatch Mountains of northern Utah under conditions of deep, continuous snowpack over unfrozen soils. The Rs factor of the USLE designed for predicting sediment losses from thaw and snowmelt greatly over estimated the actual sediment yields. Soil loss seemed to be more dependent upon the rate of snowmelt rather than the volume of melt runoff. The Rs factor (Wischmeier and Smith, 1978) was adjusted for the nonmountainous, dryland grain areas east of the Cascades in Washington, Oregon and Idaho. This adjustment of the R factor of the USLE required modification of the L and S factors (Wischmeier and Smith, 1978) as well, and all factor modifications were applicable only in the specified agricultural areas (McCool, Wischmeier and Johnson, 1982).

Rainfall simulations were conducted on laboratory plots of two cohesive soils (loam and silty clay loam) over a range of slope gradients from 3-50 percent (Singer and Blackard, 1982). Relative soil erodibility changed as slope angle increased. The S factor as calculated by the USLE did not agree with data from the two soils at the higher slope angles used in this study. This disagreement was thought to indicate slope-erodibility interactions.

Laboratory plots of California range and forest soils were used in rainfall simulations to establish their relative erodibility (Trott and Singer,1983). Results from these plot trials were compared to K factor values estimated from the USLE erodibility nomograph (Wischmeier and Smith, 1978). Results seemed to indicate that the organic matter content is not as important in the erodibility of western mountain soils as it is in the midwestern agricultural soils on which the USLE was developed.

Rainfall simulation on field plots was used to compare the potential sediment production from ten Blue Mountain ecosystems in northeastern Oregon (Buckhouse and Gaither. 1982). No unusual or severe soil disturbances were present on any of the sites. No differences in sediment production were observed between forest ecosystems. Soil loss from grassland, sagebrush and juniper ecosystems were all significantly higher than those from the forest systems.

A study on alpine soils in Rocky Mountain National Park, Colorado (Summer, 1982) compared field erodibility indices developed from rainfall simulations to laboratory analyses of aggregation, texture, organic carbon and water adsorption properties. Twenty-nine percent of the variance in erodibility was explained through aggregation and texture. This thorough comparison of laboratory and field analysis demonstrated that laboratory analyses are not an adequate method of estimating erodibility indices in alpine environments.

These studies discuss several soil properties that contribute to erodibility in the mountainous West. Many have looked at how these properties differ from those used in USLE factor calculations. Most have recognized the complexity of mountain soil environments. The failure of decades of soil erodibility research in the West to arrive at any single quantifying factor comparable to the USLE's K factor is not due to inadequate or inappropriate research, but rather it reflects the heterogeneity of the soils and of water erosion environments and processes in mountainous areas.

Thesis Objectives

This thesis study addressed the quantification of soil erodibility in the Gallatin National Forest (GNF), south of Bozeman, Montana. The GNF is a multi-management area with watersheds, timber, range, wildlife and recreation being the major uses. The sites for this study were located within two watersheds of the city of Bozeman, and were within areas of timber harvesting. The study had two major objectives:

1. To measure and compare sediment yields from rainfall simulations on two contrasting parent materials commonly occurring in the Gallatin National Forest.
2. To determine if any previous erodibility work in the intermountain West could provide sediment prediction tools applicable to water erosion environments in the Gallatin National Forest.

The first objective provided a basis on which to observe soil and site characteristics thought to influence erosion and soil erodibility. The sediment yield measurements provided the values to test the applicability of predictive models previously developed in high elevation watersheds. The second objective was pursued to determine if a usable soil erodibility prediction tool had already been developed.

Site Details

High elevation, steep, forested slopes were the site characteristics desired to represent soil erosion environments under management in the Gallatin National Forest. Two shale sites and two crystalline metamorphic sites were selected at elevations of approximately 2100 meters (7000 feet) in the northern portion of the Gallatin National Forest (Figure 1). The fine textured sites were located on late Jurassic and Cretaceous shales in the Bozeman Creek Drainage. The coarse textured sites were on PreCambrian crystalline metamorphics in the Hodgman Creek Drainage.

Three of the sites had north to northwest aspects, 35 to 45 percent slopes and were forested (Table 1). Steep shale slopes are not commonly forested in this portion of the GNF, so the fourth site chosen was a meadow area on shale slopes of 15 percent with a southwest aspect. Soil textures closely reflected their parent materials. The two shale sites were predominantly clays, silty clays, and clay loams. The crystalline sites were loamy sands and sandy loams.

Three rainfall simulator plots were located at each of the four sites, providing a total of 12 simulator plots, six plots on each parent material. Microenvironments were avoided by locating plots so they were as representative of the site location as possible in terms of slope, aspect and vegetation. Large tree roots, boulders

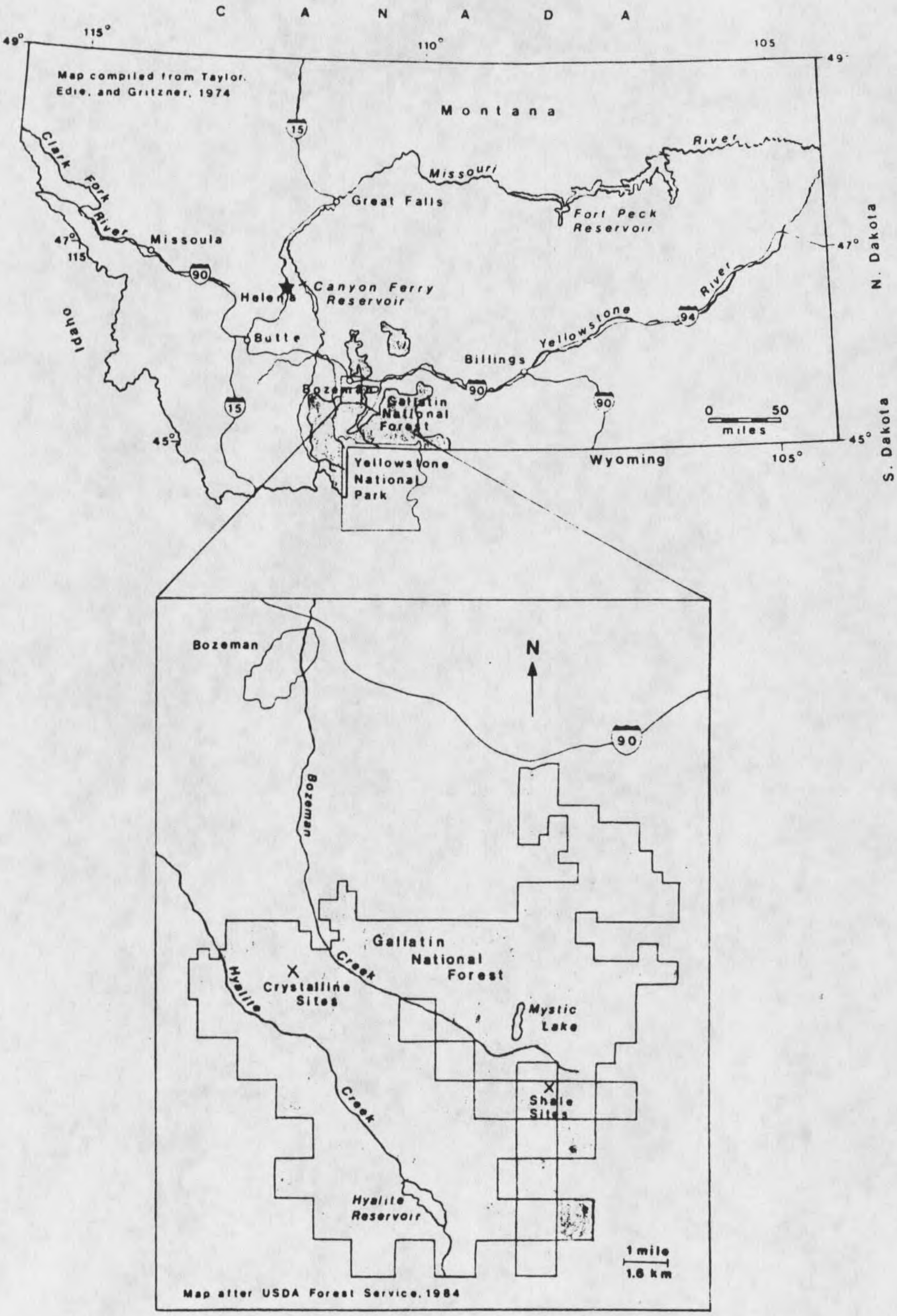

Figure 1. Location of study sites.

	M12	VSH	MER	MLP *
Location	NE 1/4, Sec 6 R7E, T4S	NE 1/4, Sec 31 R7E, T3S	NE 1/4, Sec 24 R5E, T3S	NE 1/4, Sec 24 R5E, T3S
Parent Material	Shale	Shale	Crystalline	Crystalline
Aspect	N	SW	N	NW
Slope	35%	15%	35%	45%
Elevation	2280 m (7600 ft)	2100 m (7000 ft)	2100 m (7000 ft)	2100 m (7000 ft)
Vegetation	Lodgepole Pine (*Pinus contorta*) Whitebark Pine (*Pinus albicaulis*) Subalpine Fir (*Abies lasiocarpa*)	Timothy (*Phelum pretense*) Western Yarrow (*Achillea millefolium*) [Douglas Fir (*Pseudotsuga menziesii*) adjacent]	Lodgepole Pine (*Pinus contorta*) Blue Huckleberry (*Vaccinium globulare*) Arrowleaf Balsamroot (*Balsamorhiza sagittata*)	Lodgepole Pine (*Pinus contorta*) Pinegrass (*Calamagrostis rubescens*)
Soil Textures	clay and silty clay	clay loam and silty clay	loamy sand	loamy sand and sandy loam

Table 1. Site characteristics, Gallatin National Forest, southwest Montana. *See Appendix A for explanation of site location acronyms.

and animal burrows were avoided because of their possible effects on data and also because of limitations with the simulator design.

Each of the 12 plots received three rainfall simulation runs with each run conducted on a different level of plot disturbance. The first simulator run was done on an undisturbed plot. The second run was done with the vegetation clipped and removed along with any litter layer present. The bare soil surface was not disturbed for this treatment. The final simulator run was done after the soil surface had been removed to a depth of approximately 15 centimeters (6 inches). Sediment eroded from the plot was collected for each run.

Soil samples were collected from each plot for analysis of soil water content, organic matter content, bulk density and particle size distribution. Additional plot characteristics measured were percent of ground cover and dry weight of litter removed.

METHODS AND EQUIPMENT

Rainfall Simulator

A rainfall simulator was used to monitor erosion because natural storm events are too unreliable and storm characteristics tend to be inconsistent between different locations. Even with reliable storm occurrences it can take years to collect the amount of data obtainable from a single season of rainfall simulator applications (Meyer, 1965; Hudson, 1981).

Erosion studies done with portable rainfall simulators are limited to looking at only the interrill stage of erosion (Gifford, 1986). Transport and deposition of detached particles are limited by the small plot sizes associated with portable machines, and the more advanced stages of rill and gully erosion are not attained.

The interrill stage of erosion is dominated by drop impact (Hudson, 1981; Meyer, 1985), where the drop impact is responsible for both soil particle detachment and transport (Quansah, 1981; Kneale, 1982). The major factors affecting erosion rates under drop impact are soil type, precipitation intensity and soil surface coverage (Meyer, 1985). Precipitation intensity and soil surface coverage are directly measurable. The soil variable in interrill erosion can be equated with soil erodibility. The focus of a rainfall simulator study on interrill erosion is then a focus on soil erodibility.

The erosive energy of rainfall is usually calculated in terms of kinetic energy (KE = 1/2 M V^2) rather than strictly in terms of intensity (Wischmeier et al, 1958; Hudson, 1981; Quansah, 1981). The velocity term used in calculating kinetic energy reflects storm intensity. Storms of different intensities have different distributions of raindrop sizes (Laws and Parsons, 1943). The size of a water drop influences the velocity with which that drop will fall (Laws, 1941; Gunn and Kinzer, 1949; Best, 1950), so intensity is reflected in kinetic energy calculations through the influence of drop size on velocity.

Terminal velocity is not readily attainable in the field with many portable rainfall simulators (Young, 1979; Hudson, 1981). Calculations of kinetic energy can be used to compare the energy of a natural storm to that of a simulated rainfall event (Gifford, 1979). Simulated drop size and fall height must be known in order to estimate impact velocity for the simulated precipitation.

The rainfall simulator used in this study was a modified Meeuwig drip-type simulator (Meeuwig, 1971b) (Figure 2) with a drop fall height of 155 cm (62 inches). The approximate waterdrop diameter at a simulated intensity of 127 mm (5 inches) per hour was 2.8 mm (0.11 inches) (Gifford, 1986; Appendix B). Impact velocity for a 2.8 mm waterdrop falling 155 cm is approximately 470 centimeters (15 ft) per second (Laws, 1941). Terminal velocity (impact velocity) of this size

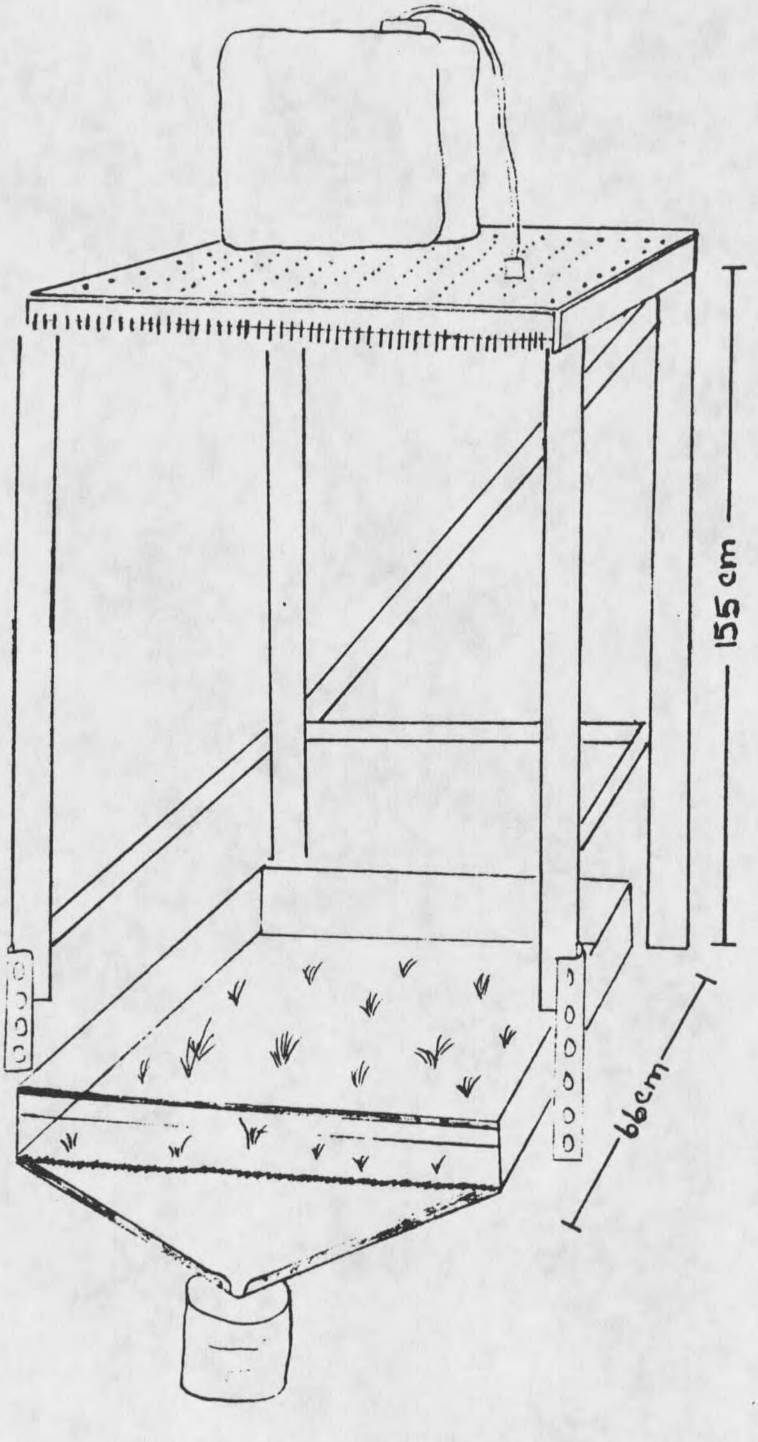

Figure 2. Sketch of rainfall simulator.

drop in a natural storm is 780 centimeters (26 ft) per second (Gunn and Kinzer, 1949).

For this study, the simulated rainfall events had a kinetic energy that was roughly one-third that of equal intensity natural storm events. The 2.8 mm diameter drop was approximately equal to the average drop size for a natural storm with an intensity of 127 mm per hour (Laws and Parsons, 1943; Hudson, 1981). It is then a reasonable assumption that the mass of waterdrops for the simulated events in this study at 127 mm per hour was approximately equal to the mass of a natural storm of the same intensity. The comparison of kinetic energy between the simulated events and natural storms then becomes a ratio of drop impact velocities (V^2[simulated] ÷ V^2[natural]) (Appendix B).

The modified Meeuwig (1971b) simulator used in this study had a 61 cm by 61 cm by 2.5 cm (24 by 24 by 1 inch) plexiglass water chamber with approximately 500 drip needles made from hypodermic tubing. This water chamber was rotated horizontally by an electric motor to prevent the waterdrops from falling repeatedly in the same position on the plot below. The frame holding the water chamber was adjustable allowing the water chamber to be leveled over any slope angle.

An 18.9 liter (5 gallon) reservoir was elevated 20 cm (7.9 inches) above the water chamber. This height maintained a relatively constant head on the water in the chamber, and supplied enough water to the chamber to conduct a 30 minute simulator run at a constant intensity of 127 mm per hour. Distilled water was used for all simulator runs to ensure a known water quality that would not clog the drip needles and would prevent any undesirable chemical reactions with the soil particles in the plots.

A 66 cm by 66 cm (26 by 26 inches) plot frame was pounded 2 to 5 cm (0.75 to 2 inches) into the soil to reduce lateral movement of water out of the plot. The down slope side of the plot frame was open to allow movement of water runoff and detached sediment onto a collection tray which funneled the water and eroded sediment into a collection can. The plot frame was made larger than the water chamber to accommodate the area covered by the horizontal rotation of the chamber.

The plot edge of the collection tray had a 1.27 cm (0.5 inches) flange that was inserted into the soil until the tray was level with the soil surface inside the plot frame. Dry, powdered bentonite was used to seal the tray edge to the plot. This prevented water and detached sediment from flowing under the tray instead of into the collection can. The surface of the bentonite became fairly smooth when it became wet, so movement of water and sediment from the plot to the tray was negligibly interrupted.

The first 30 minute simulator run, or litter run, was conducted without any disturbance to the plot surface. All vegetation and litter on the soil surface were left undisturbed. A 2.54 cm by 5 cm (1 by 2 inches) rectangular microplot sampler (Morris, 1973) was used to record the percent of soil surface covered by litter, vegetation, or moss. The rectangle was placed and percent basal cover was recorded at ten equally spaced locations across the diagonal of each plot. These ten readings were averaged to determine the percent of ground cover for each litter run.

The second simulator run, or bare run, was done immediately after the litter run was completed. The plot frame and collection tray were left in place, but all vegetation was clipped and removed along with all litter. All vegetation and litter removed from each plot was taken back to the laboratory and air-dried to a constant weight.

The soil surface itself was undisturbed and bare except for any roots and rocks that were present. Visual estimates were made throughout the 30 minute period of how much of the exposed plot surface was covered by roots and rocks along with their approximate sizes.

The final 30 minute simulator run, the subsurface run, required removal of the plot frame and collection tray. Immediately after completion of the bare run, the plot was dug out to a depth of approximately 15 cm (6 inches), which was below the soil A horizon at all plot locations. The plot frame and collection tray were then reinstalled at the new soil surface level, and the soil surface inside the plot frame was gently smoothed to remove any artificial sediment storage areas. Visual estimates of rock and root size and coverage were again recorded throughout the 30 minute run.

Eroded sediment and water runoff were collected for each of the 30 minute simulator runs. The sediment did not settle out of all samples after 24 hours, so each sample was flocculated with enough $CaCl_2$ to approximate a 0.01 molar solution and then allowed to settle for another 24 hours. Most of the water could then be siphoned from the settled sediment. The remaining water-sediment slurry was oven-dried to a constant weight before a final weighing of the amount of sediment eroded from each plot.

Soil Samples

Water Content

Soil samples were taken from the soil surface adjacent to each plot prior to the litter runs to determine soil water content. These samples were taken from the area where the collection tray and can were installed in order to get as close to the plot as possible without disturbing the plot surface. Sampling depth averaged 2.5 cm (1 inch) with a maximum depth of 5 cm (2 inches). Any litter on the soil surface was not incorporated into these samples, so the sampling reflected the soil water content, not necessarily the water content of the drop impact surface.

Samples to determine the soil water content of the bare runs were taken after the vegetation and litter were removed. These samples were taken from the soil surface directly outside the plot frame where rotation of the water chamber had rained on areas outside the plot frame.

Thick litter layers on some plots prevented the litter run water from reaching or significantly wetting the soil surface. This was suggested by the lack of eroded sediment from the litter run and was visually obvious when the litter layer was removed and the soil surface exposed for the bare run. In these cases, no additional sample was taken for the bare run soil water content. That sample taken prior to the litter run represented the soil water content for both the litter and bare runs on that plot.

Soil water content samples were taken at similar depths and locations to those of the litter run when the new soil surface level was exposed for the subsurface runs on each plot.

All soil water content samples were returned to the laboratory as soon as possible. They were then weighed wet, oven-dried to a constant weight, and reweighed to determine percent water content on a weight basis.

Organic Matter

Each plot was sampled twice for organic matter determinations. One soil sample was taken from the 0 to 2.5 cm (0 to 1 inch) depth and the second at a depth of 2.5 to 5.0 cm (1 to 2 inches). These soil samples were kept as cold as was practical and were returned to the laboratory as soon as possible where they were oven dried to a constant weight. The samples were then sieved to remove coarse fragments and the fine fraction was ground in a Dynacrush soil grinder. The ground samples were then analyzed by a modified Walkley-Black method according to procedures defined by Sims and Haby (1971). This organic matter content determination was done on a Spectronic 20 colorimeter.

Bulk Density

Soil samples were taken by the core method (Blake, 1965) from each plot at a 0 to 10 cm (0 to 4 inch) depth for measurement of bulk density. These samples were taken by pounding a 7.5 cm (3 inch) diameter sampling can into the side of each plot after it had been excavated to the subsurface level. The bulk density samples were weighed wet, oven dried to a constant weight, reweighed, and then sieved to remove all coarse fragments greater than 2 mm (0.08 inches) in diameter and all roots.

The roots and rocks were weighed separately in order to determine their respective volumes within the soil sample. Coarse fragment volumes were calculated using the standard 2.65 grams per cm^3 density and root volumes were calculated using a density of 0.5 grams per cm^3. Subtracting these volumes from the total sample allowed a calculation of the soil fine fraction bulk density.

Particle Size Distribution

Surface and subsurface level soil samples for particle size distribution were taken at each plot. The samples were oven dried and them sieved to remove all coarse fragments greater than 2 mm in diameter. The shale samples were wet sieved to prevent shale coarse fragments from being broken into pieces smaller than 2 mm by grinding in a mortar and pestle. These samples then had to be re-dried before the final hydrometer analysis.

The hydrometer analysis was done according to the American Society of Agronomy (ASA) standard methods (Day, 1965) with two exceptions:

1. Samples mixed with Calgon were allowed to soak overnight rather than ten minutes, and were agitated for two minutes rather than five. The high clay content of some samples required the longer soaking time for adequate dispersion. The longer period of dispersion required a shorter agitation time, which also was less abrasive on sand-sized particles (Bouyoucos, 1962).

2. Sample sizes of 50 grams were used for the shale soils, and samples of up to 100 grams were used for the high sand samples. The extreme range of particle sizes present in the soils required larger sample sizes (Bouyoucos, 1962; Gee and Bauder, 1986).

Hydrometer readings on all samples were taken at the following time intervals:

40 seconds
60 seconds
3 minutes
10 minutes
30 minutes
60 minutes
90 minutes
2 hours
4 hours
12 hours
24 hours

All hydrometer samples for the crystalline sites were re-agitated and the 40 and 60 second readings taken a total of three times. The three readings were then averaged for each sample. These readings were the most susceptible to error because of how rapidly sand sized particles settle and how quickly the readings must be taken. The averaged reading should have yielded a more accurate representation of the high sand content of these samples.

After completion of the hydrometer readings, all samples were wet sieved, redried, and reweighed to determine distribution of very coarse, coarse, medium, fine, and very fine sand sizes particles. Sieve sizes used corresponded to particle diameters of:

1.00 to 2.00 mm	(0.039 to 0.079 inches)
0.50 to 1.00 mm	(0.020 to 0.039 inches)
0.25 to 0.50 mm	(0.010 to 0.020 inches)
0.10 to 0.25 mm	(0.004 to 0.010 inches)
0.05 to 0.10 mm	(0.002 to 0.004 inches)

Site Observations

Slope and aspect measurements were taken at each site using a clinometer and compass. Site elevations were estimated using USGS topographic and geologic maps. Dominant vegetation was also identified at each site. Soil pits were dug at each site and characterized with standard Soil Survey (1975) observations (Appendix C).