ESTIMATES OF UPLAND EROSION AND RUNOFF IN AN ARID WATERSHED IN WYOMING

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ABSTRACT

Rainfall simulation experiments were conducted in the Fifteenmile Creek watershed of north-central Wyoming to identify nonpoint sources of suspended sediment. A portable drop-forming rainfall simulator was chosen for reasons of low cost and low water requirements. Simulated rainstorms were applied to 73 study plots for a duration of 1 hour. Rates of erosion and runoff were found to be most closely related to vegetation density, litter density, slope gradient, and soil texture. Erosion and runoff production were then related to composite terrain types to facilitate data analysis and display in a geographic information system.

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INTRODUCTION

Controlling watershed sediment production has become a focus of present day nonpoint source pollution control strategies and is of particular concern in semiarid environments where natural rates of sediment production are at their highest. Excessive sediment concentrations can increase domestic water treatment costs, damage crops, add to maintenance costs for irrigation systems, degrade fisheries resources, and result in decreased reservoir storage capabilities. Also, nutrients, pesticides, and biological pollutants are often transported by fluvial sediments (Novotny and Chesters, 1981).

The quantity of sediment discharged at the outlet of a drainage basin system is ultimately related to the supply of sediment and runoff produced by upland sources. Numerous geomorphic processes act to remove sediment from uplands including rainsplash, sheet erosion, slumping, mass wasting, piping, rilling and gullying. Physical characteristics, especially climate, topography, living or dead vegetative cover, and soil type, can control the effectiveness of these processes. Human activity can also influence the amounts of runoff and sediment produced by a watershed. Grazing animals can cause soil compaction, resulting in reduced infiltration rates and increased overland flow (Branson et al. 1981). Also, removal of plant cover by grazing animals can result in increased sediment yields by exposure of soils to erosive forces (Lusby 1970). Roads and off-road vehicle trails can also cause increased sediment production in a watershed.

In the Fifteenmile Creek watershed of northcentral Wyoming, suspended sediments are considered the major water quality problem. The basin contains all of the characteristics associated with high sediment yields including an arid climate, erosive soils, low vegetative cover, and often steep slopes. The Big Horn Basin 208 Water Quality Plan identified Fifteenmile Creek, an ephemeral stream, as the largest contributor of sediment to the Big Horn River (Cooper 1979). In addition, the Bureau of Land Management (1950) identified Fifteenmile Creek as the primary watershed in need of erosion control measures (Skinner et al. 1982).

In the early 1960's, the Bureau of Land Management (BLM) began an aggressive watershed improvement program to control sediment production from the basin. Work undertaken by the program included the installation of sediment retention structures, water spreaders, drift fences, revegetation attempts, and altered grazing management practices (Cooper 1979). Yochem and Rosenlieb (1978) evaluated changes in downstream suspended sediment concentrations in response to these measures using 20 years of streamflow and sediment data from a gaging station located on Fifteenmile Creek near its confluence with the Bighorn River. They concluded that a 25 percent reduction in sediment concentrations could be directly related to the watershed improvements. However, recent on-site inspections revealed that many of the structures are now failing.

This research will focus on runoff production, and sediment production from rainsplash and sheet erosion, the initial hydrologic forces acting on a watershed ultimately determining the supply of sediment and energy to other components of the system, and the physical characteristics which determine the effectiveness of these fluvial processes. The objectives of the study are to investigate factors influencing the production of sediment and runoff in upland areas of the basin, and to identify terrain types in the basin and quantify the relative contributions of these terrain types to the total watershed sediment supply. Methods used will be rainfall simulation and computer assisted mapping. These findings will then be used in conjunction with basin geomorphology and channel capacity data to develop a model outlining the mechanisms responsible for the erosion transport and deposition of sediments within the basin.

Since the research will quantify the relative contributions of various sources to the sediment budget of the basin, the generated information will be useful to land management agencies such as the Bureau of Land Management when developing strategies to decrease sediment discharge from the watershed. This study on upland sediment production will serve to complement research by the University of Wyoming Range Management Department analyzing the impact of livestock grazing in riparian zones along Fifteenmile Creek (Skinner et al. 1985). In short, the information will allow land managers to concentrate their efforts and financial resources on those variables having the greatest influence on the ultimate rate of sediment supply from the hillslopes in the basin and on those areas of the basin which contribute disproportionately to the sediment supply.

DESCRIPTION OF THE STUDY AREA

The Fifteenmile Creek watershed is located in the Big Horn Basin of northcentral Wyoming, a 1350 square kilometer (520 square mile) rain-shadow area bordered by the Absaroka Range to the west and the Big Horn Mountains to the east (Figure 1). The basin is a cold desert environment with a median elevation of 1500 meters (4900 feet). Average annual

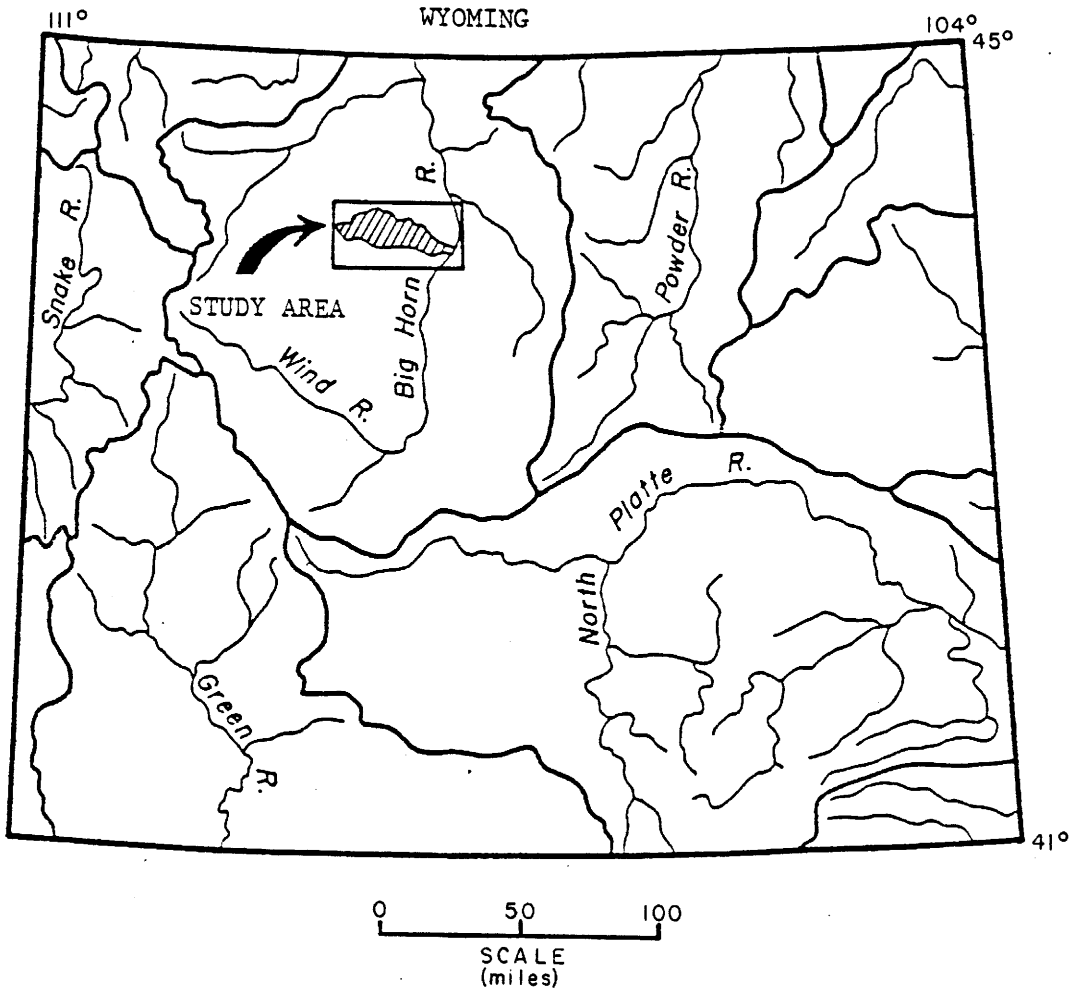


Figure 1. Location map of the Fifteenmile Creek watershed study area.

precipitation is 20.3 cm (8 inches) of which approximately 10 percent is snowfall and 40 percent falls during the summer months (Martner 1987). The mean annual temperature is 7°C (45°F) ranging from a mean daily low of -16°C (4°F) in January to a mean daily high of 32°C (90°F) in July (Martner 1987).

Geology

The geology of the basin is largely the result of extended periods of sediment deposition. Eocene claystones and sandstone deposits of the Willwood Formation and Quarternary alluvial deposits underlie the lower portions of the basin while claystones and shales of the Eocene Tatman Formation dominate the geology of the higher elevation western portions of the basin (Lowry et al. 1976). Outcrops of the Willwood formation form extensive badland areas in portions of the basin. These badland areas are characterized by highly erosive strata, steep slopes, little vegetation, and an extremely dense drainage network. Rates of erosion and runoff production in these zones are expected to be extremely high.

Soils

Soils in the watershed are diversified and generally poorly developed due to the limitations imposed by the arid environment. A BLM-SCS soil survey of the area completed in 1979 describes the basin soils (Knox et al. 1979). Soils range from clayey to sandy as a function of varying parent materials such as shale, mixed alluvium, siltstones, and sandstones. In addition, the soils are often poorly leached, resulting in high salt and carbonate concentrations that can inhibit plant growth.

Vegetation

Plant communities in the basin are dominated by shrubs, grasses, forbs, and cactus. Sagebrush (*Artimesia* spp.) and saltbush (*Atriplex* spp.) are the predominate shrub types found in upland areas. Blue grama (*Bouteloua gracilis*), a sod forming grass, and rhizomatous wheatgrasses (*Agropyron* spp.) are the prevailing grass species in many areas of the watershed often occupying the interspaces between shrubs. Prickly pear cactus (*Opuntia polycantha*) also provides ground cover on the upland flats in association with shrubs and blue grama. Other bunchgrasses, annual grasses, and forbs add diversity to the plant communities of the basin. Vegetation in the basin is often sparse and many areas are devoid of plant cover.

Human Uses

Human uses of the watershed include oil and gas production and exploration, recreation, and livestock grazing. The degree to which livestock grazing has altered the prehistoric plant communities of the Big Horn Basin has not been well established. Dorn (1986) used historical data to conclude that vegetation cover and composition have been essentially unchanged. The potential for nonpoint pollution from mining in the basin is fairly low due to the small amount which occurs (Cooper 1979). Recreational uses in the basin, such as off-road vehicle use, have the potential to alter sediment production and runoff. Grazing by wildlife is another possible impact to the watershed.

EROSION AND RUNOFF

Rainsplash Erosion

The detachment of soil particles under the impact of raindrops is the initial hydrologic force acting on the surface of the earth. Factors influencing the extent of rainsplash erosion include the frequency, duration, and intensity of precipitation, local topography, properties of the soil surface, and the degree to which the soil surface is protected by vegetative cover and other organic materials (Branson et al. 1981). In short, the magnitude of rainsplash erosion will vary from storm to storm and spatially within the basin. Any attempt to quantify its magnitude will need to consider all of these variables and the degree to which they can be measured. The extent to which any such findings could be applied spatially will also depend on the degree of measurement and be subject to practical constraints when evaluating entire drainage basins.

As raindrops strike the earth, soil particles disaggregate and are scattered in all directions away from the point of impact. The majority of the detached soil particles will move in a downslope direction and the distance they are displaced will be a function of the particle size, and the energy produced by the falling raindrop. This can in turn lead to a selected sorting of the soil as finer particles are more likely to be removed and displaced further downslope (Zachar 1982).

To understand the erosivity of rainfall, one must first examine the kinetic energy produced by the falling drops. Laws (1941) measured the fall velocity of raindrops and quantified the velocity of these drops with regard to their size and height of fall. Using these data in addition to the calculated mass of the raindrop, the energy for a raindrop can then be calculated using the equation for the kinetic energy E of a mass m moving with a velocity v:

$$E = 1/2\ mv^2. \quad (1)$$

Knowing the intensity of the rainfall, mean drop size, and storm duration, it is then possible to calculate the kinetic energy per unit area produced by a storm. However, natural rainfall seldom produces drops of uniform size, with the mean drop sizes usually varying in response to rainfall intensity (Laws and Parsons 1943).

In response to this problem, Wischemeier and Smith (1958) developed a simple procedure for computing the kinetic energy of a rainstorm from the information obtained from a recording-raingage chart. The equation was developed using data correlating drop size with rainfall intensity and takes the form:

$$Y = 916 + 331 \log 10X \quad (2)$$

where: Y = kinetic energy (ft tons/acre)

X = rainfall intensity (inches/hour).

This equation is widely accepted and used in calculating the rainfall factor (R) for the universal, and modified soil loss equation (Mulkey 1980; Wischemeir 1959).

Runoff

Runoff (surface runoff) is an indicator of interception, depression storage, and infiltration. Before reaching the soil surface, rainfall can be intercepted by vegetative cover or litter with the amount of interception being a function of the type and density of vegetative materials. Once the rainfall reaches the soil, much of it is absorbed through the process of infiltration. The rate of infiltration is determined by the physical properties of the soil. When the rate of rainfall exceeds the infiltration rate, or the soil becomes saturated, water will begin to pond on the surface in depressions or begin to flow downslope. Consequently, runoff occurs when opportunities for interception and depression storage are exhausted and the rainfall rate exceeds the infiltration rate (Branson et al. 1981). Runoff is important because it supplies energy to cause sheet, rill, gully, and channel erosion and transports eroded sediments.

Sheet Erosion

If the amount of rainfall exceeds that lost to depression storage and interception by both living and dead vegetative matter, and if the rainfall rate exceeds the rate of water the soil can absorb through infiltration, surface runoff and resulting sheet erosion will occur. As is the case with rainsplash erosion, sheet erosion will often be selective towards finer soil fractions, thereby sorting materials on the soil surface. As slopes steepen and length of slope increases, the velocity of sheetflow will also increase resulting in excessive turbulence of flow and an end to sheet erosion as the surface runoff concentrates into defined channels or rills. Eventually, larger channels such as gullies and streams will form. Much of the soil removed by rainsplash and sheet erosion will be redeposited before reaching a defined channel.

RAINFALL SIMULATION

Rainfall simulation is the technique of applying water droplets to a plot in a way that mimics natural rainfall and is often used as a means of determining rates of infiltration and soil erosion under controlled conditions. Depending on their size and that of the experimental plot, rainfall simulators can be used to measure rainsplash, sheet, and rill erosion. Simulators are particularly useful in studies when the study duration is limited and in areas that receive precipitation infrequently.

Types of Rainfall Simulators

A variety of rainfall simulators have been tested over a wide range of experimental conditions in the United States during the past half century. All simulation units consist of a water supply, a drop forming device, a plot, and a device for collecting the resulting runoff and sediment. The method of drop formation is usually used to distinguish rainfall simulators dividing them into two broad categories: 1) those using spray nozzles, and 2) those that employ drop formers.

Spray nozzles that have been used in rainfall simulation range from sprinkler cans to slotted rotating disks. Most modern spray nozzle simulators, however, use jet-type nozzles where the water is forced through under pressure. Earlier simulators generally were built with the spray nozzles pointed up, with the drops reaching a determined height and then falling in response to gravity. More recent trends have been to point the nozzles downward to attain higher impact velocities which approach the terminal velocities of natural raindrops (Meyer 1979). The ability to produce higher drop velocities and generally larger plot sizes is an advantage of spray nozzle type simulators. However, spray nozzle type simulators are often cumbersome, require pumping units, have high water consumption rates, and often are not capable of producing drops of uniform size and spatial distribution. Examples of spray nozzle type simulators include: the Rocky Mountain infiltrometer, a portable simulator unit designed for measuring infiltration on western forest and rangelands (Dortignac 1951); the programmable Lafayette rainulator, a simulator developed for use on field plots which can be programmed to produce artificial storms of varying intensities (Foster et al. 1979); and the Palouse rainfall simulator, a simulator developed to mimic low intensity storms (Bubenzer et al. 1979).

Types of drop formers used to produce artificial rain drops include: yarn, hypodermic needles, glass tubes and plastic tubing, with plastic tubing being most commonly used. Drops form on and adhere to the drop former tip until the weight of the drop overcomes the surface tension to the tip and the drop falls, the size of the drops being controlled by surface tension and the size of the drop former. The drop formers are typically mounted in a module with the rate of drop formation controlled by the head of water on the module. Simulators using drop formers have the advantage of generally being portable, producing drops of consistent size and spatial distribution, and allowing the operator to rapidly change rates of distribution. However, the large number of drop formers required per plot area limits the practical size of drop forming simulators. Also, the tips must be supported high above the plot for the drops to approach their terminal velocities (Table 1). Examples of rainfall simulators that use tips to form drops are: the Tahoe Basin rainfall simulator, a portable rainfall simulator for field study of erosion potential and infiltration on mountainous terrain (Munn and Huntington 1976); the University of Illinois laboratory simulator, a laboratory rainfall simulator designed to produce controlled simulated

Table 1. Fall velocity of water drops in still air (Laws 1941)

Drop Diameter (mm)	Fall Distance (m)							
	1.00	2.00	3.00	4.00	5.00	6.00	8.00	20.00 (terminal)
	Fall Velocity (m/sec)							
1.5	3.64	4.50	4.99	5.25	5.39	5.47	5.51	5.51
2.0	3.83	4.92	5.55	5.91	6.15	6.30	6.35	6.58
2.5	3.98	5.19	5.89	6.34	6.67	6.92	7.22	7.41
3.0	4.09	5.37	6.14	6.68	7.08	7.37	7.75	8.06
3.5	4.15	5.52	6.35	6.95	7.40	7.73	8.15	8.52
4.0	4.21	5.63	6.52	7.17	7.65	8.00	8.46	8.86
4.5	4.24	5.72	6.66	7.36	7.85	8.21	8.70	9.10
5.0	4.27	5.79	6.77	7.50	8.00	8.36	8.86	9.25
5.5	4.29	5.85	6.86	7.61	8.11	8.47	8.97	9.30
6.0	4.31	5.90	6.94	7.69	8.30	8.55	9.01	9.30

storms of flexible intensity and duration (Chow and Harbaugh 1965); and a mobile drip type infiltrometer used to measure infiltration rates and sediment production on rangelands described by Blackburn et al. (1974).

Comparing Natural and Simulated Rainfall

Several studies have attempted to compare natural and simulated rainfall. Barnett and Dooley (1972) compared the erosion potential of natural and simulated rainfall using a spray nozzle type simulator developed by Meyer and McCune (1958) and found it to produce an average rainfall energy equal to 75 percent that of natural rain at 2.5 inches per hour. Young and Burwell (1972), using a similar device to predict runoff and erosion from natural rainfall, found that soil losses from simulated storms averaged 77 percent those produced by natural storms. Bubenzer and Jones (1971) used a drop forming rainulator to test the effects of drop size and impact velocity on the detachment of soils by simulated rainfall. Because of the length of slope required for erosion by overland flow, Romkens (1979) cautioned against using simulators covering experimental plot areas less than 100 sq. ft. for direct evaluation of the Universal Soil Loss Equation.

Literature Review of Research Involving Rainfall Simulation

Most relevant to this research are studies that have used rainfall simulation to evaluate rates of erosion and runoff production in semi-arid watersheds. Blackburn and Skau (1974) used a mobile type drop forming simulator to evaluate sediment production and infiltration for 29 plant communities in Nevada rangelands. Infiltration rates and sediment production were found to vary considerably, and the highest infiltration and lowest sediment production were found to be associated with well-aggregated surface soils. Bryan and Hodges (1981) used simulated rainfall in combination with an understanding of basin lithology to evaluate sediment transport dynamics in a Canadian badland microcatchment. They concluded that rainsplash plays an important role in sediment entrainment, but the dominant mode of sediment transport is surface and subsurface runoff. Using a spray nozzle type rainfall simulator on northern Utah rangelands, Meeuwig (1970) emphasized the importance of vegetation and litter cover in maintaining infiltration capacity and soil stability. Employing a drop forming rainfall simulator on rangelands in southern Alberta, Johnson (1962) found infiltration to be directly related to range condition with infiltration rates increasing positively with vegetation and litter cover. However, his findings concluded that soil loss did not change significantly with moderate grazing. Imenson (1983) evaluated sediment loss from small plot experiments in a semiarid area of northern Morocco and found microtopographic roughness to exert a greater effect on runoff and soil loss than the infiltration characteristics of the soil. Wood and Blackburn (1981) examined the effects of grazing systems on infiltration rates on the Rolling Plains of Texas and found infiltration rates to be similar across grazing treatments of heavy and moderate stocking. Comparing infiltration rates and sediment production on fertilized and unfertilized grazed blue grama rangeland, Wood et al. (1986) concluded that infiltration and sediment production did not differ between fertilized and unfertilized rangeland, although livestock production and stocking rates were twice as great on the fertilized rangeland.

GEOGRAPHIC INFORMATION SYSTEMS

Geographic information systems can be used to store, retrieve, update, combine, manipulate, and display spatial data. As computer digitized terrain data become more available, and with the rapid advances being made in geographic information systems, generating computer maps for watershed management purposes offers and expanding field of study for geographers. Maps generated by such systems can be useful in conveying information between professional and nonprofessional audiences. They can also be used in locating those areas of a watershed that are of particular concern to land managers and to assess the possible implications of proposed land management strategies.

There are two primary types of maps produced by geographic information systems: raster and vector (Monmonier 1982). Raster maps display spatial data by use of a grid or matrix with values assigned to each element in the grid. Vector maps use a coordinate system to locate points and create lines which enclose areas into polygons. Data are assigned to the elements in the raster grid or the polygons in vector maps for processing and display. Algorithms can then be developed and used to manipulate these data.

To date, limited research has been performed in the water resources field utilizing geographic information systems. Gilliland and Baxter-Potter (1987) used a geographic information system to predict nonpoint source pollution from suspended solids and coliform bacteria in Nebraska. Vold et al. (1985) created polygon maps and algorithms to estimate soil erosion potentials in British Columbia. Svatos (1979) used a geographic information system to analyze potential water quality problems caused by land development in Delaware. The research involved use of a grid cell data file and algorithms to identify those land areas which, if disturbed, would have the greatest impact on water quality.

METHODS

Rainfall Simulator

Because of the logistical constraints of the research project, a rainfall simulator design was chosen to meet the following criteria: rainfall characteristics similar to those of natural rainfall, portability, low water consumption, ease of operation, and low cost. The simulator, constructed for this project utilized the plexiglass chamber concept developed by Chow and Harbough (1965) and is similar structurally to the Tahoe Basin rainfall simulator developed by Munn and

Huntington (1976). The design selected for this research, dubbed the "Big Horn Basin" rainfall simulator, is durable, light in weight, easy to set up, capable of being operated on steep slopes (up to 60%) with moderate winds, and has low water consumption. Figure 2 illustrates the instrument.

The most important feature of the simulator design is the 0.61 x 0.61 meter (2 x 2 foot) modular plexiglass rainfall chamber. Embedded in the chamber are 576 polyethylene tubing tips with a .058 cm (0.023 inch) inside diameter and .097 cm (0.038 inch) outside diameter which produce 3.2 mm water drops. The rate of water entering the rainfall chamber from the water reservoir and resulting rate of drop formation is controlled by a variable area flow meter. A 25 liter (5 gallon) reservoir, located on a platform above the drop forming chamber, serves as a water supply.

The stand for the rainfall chamber is constructed of lightweight aluminum plate and square tubing with the upper portion being extendable. By extending the upper portion of the stand and by raising or lowering the legs of the apparatus, the height of drop fall can be adjusted from 1.8 to 2.6 meters (6 to 8.5 feet). The adjustable legs, constructed of steel thread rod, are also used for leveling the simulator on slopes. Plywood sides were installed on the simulator stand to shield the falling drops in light to moderate winds. However, a small area around the top of the simulator was left unshielded to allow some turbulence to enter and randomize the drop distribution pattern. A gutter trough near the base of the structure captures any drops falling outside the defined plot area.

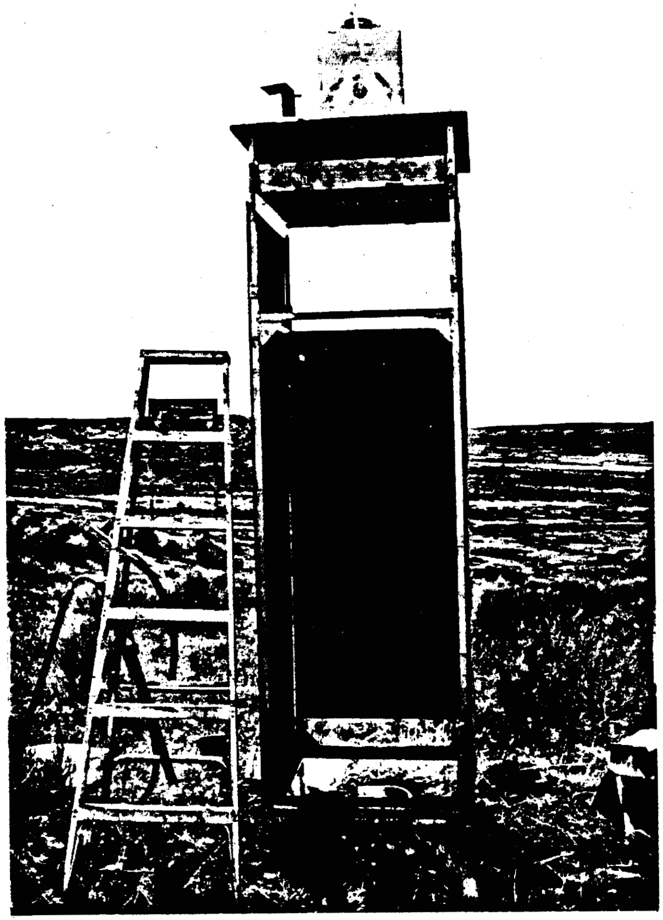


Figure 2. The Big Horn Basin Rainfall Simulator.

A sheet metal border was used to define the plot perimeter. At the downslope end of the plot, a funnel trough was placed to direct runoff and sediment into collection containers (Figure 3). A sheet of galvanized metal was also used to cover and protect the plot while setting up for an experiment.

Energy Characteristics of the Simulated Rainfall

The simulator produces 3.2 mm drops which fall from a height of 2.3 meters (7.5 feet). The maximum velocity of these drops is 5.69 meters per second (18.7 feet/second) and solving for Equation (1) produces a kinetic energy of .000279 joules per drop.

A storm intensity of 7.61 cm/hr (3.0 inches/hour) for a duration of 1 hour was chosen for the experiments. This intensity was selected because it was found to represent a minimum rate of flow required for adequate drop formation by the instrument. The total kinetic energy produced by these storms for each study plot was 456 joules, equivalent to 1850 foot tons/acre. Solving Equation (2) for a simulated storm of this energy produces an equivalent natural 1-hour duration storm of 4.70 cm (1.85 inches). This is similar to the 3.56 cm (1.4 inch) 50-year/ 1-hour event for Worland, Wyoming.

Selecting Study Sites

In the spring of 1987, mapping was undertaken to outline areas of the basin into categories of similar slope, vegetation, and soil types. Slope was determined from U.S. Geological Survey 1:24000 scale topographic maps using the contour spacing method (Marsh 1983). The slope zones were then delineated into six categories.

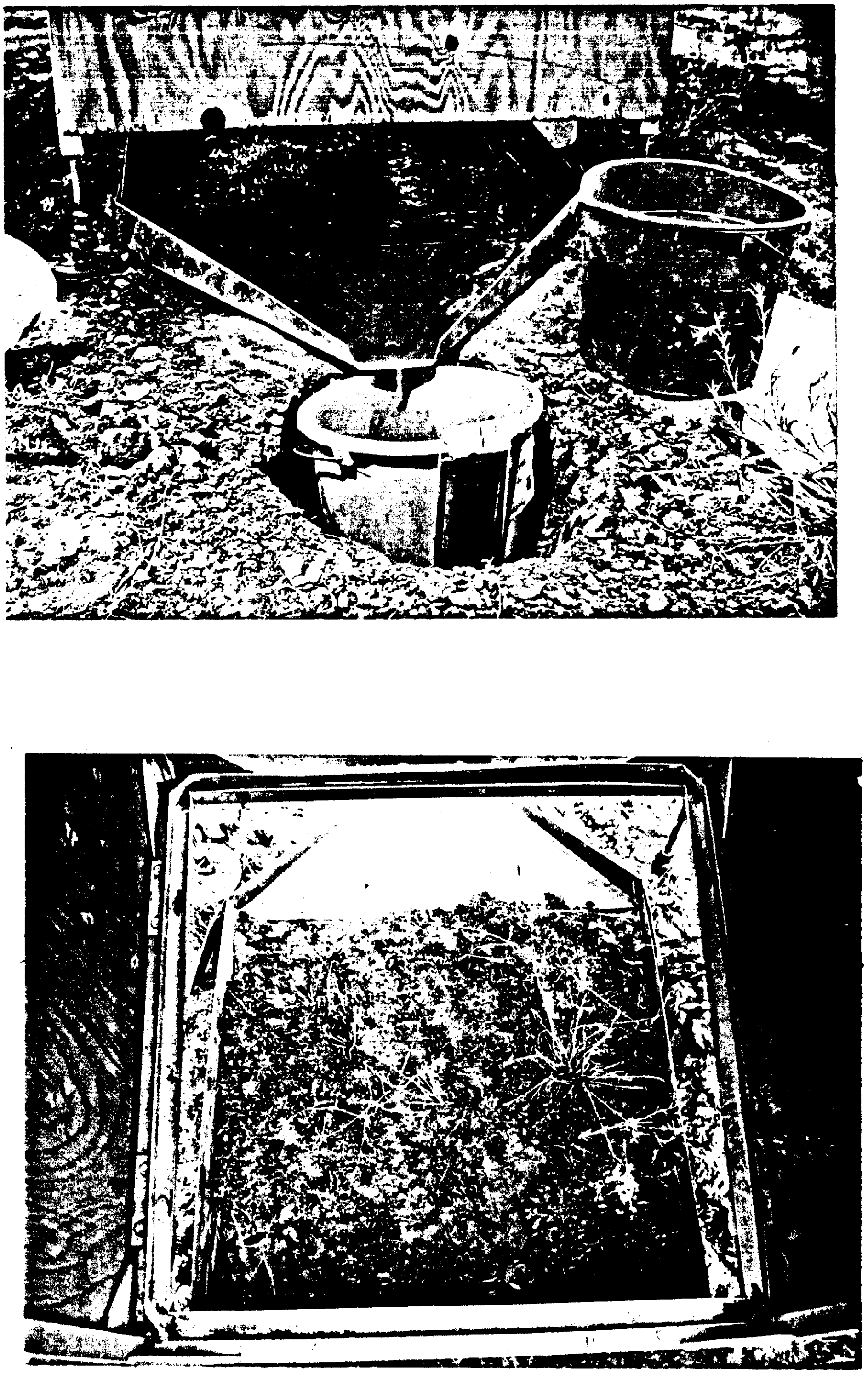


Figure 3. Funnel trough and plot perimeter.

A = 0-2% (0 - 1.5)

B = 2-5% (1.5 - 2.9)

C = 5-15% (2.9 - 8.5)

D = 15-35% (8.5 - 19)

E = 35-55% (19 - 29)

F = >55% (>29)

Vegetation and soil types were determined from Bureau of Land Management site write-up area (SWA) maps which contain a composite of soil associations, vegetation composition (at the community level) and ecological condition class.

Because of the large size of the watershed, study sites were concentrated in the 109 km^2 (41.8 mi^2) Middle Fork subbasin (Figure 4). From the maps and visual inspections in the field, 37 sites were selected, 36 in the Middle Fork subbasin and 1 in the lower main basin, to be representative of the varying soils, vegetation densities, and topographic regions found in the watershed (Figure 5). The sites were also chosen to comprehensively cover the basin, although poor access limited sampling in some areas.

At each study site, except for site 35, two rainfall simulation experiments were conducted for a total of 73 study plots. This was done to increase the sample size. All simulation experiments were performed in July and August of 1987.

Field Experiments

Access to the basin was restricted to an unimproved road and two-track trails. A 3/4 ton 4-wheel-drive truck was used to transport the simulator, water supply, and other necessary equipment to the study

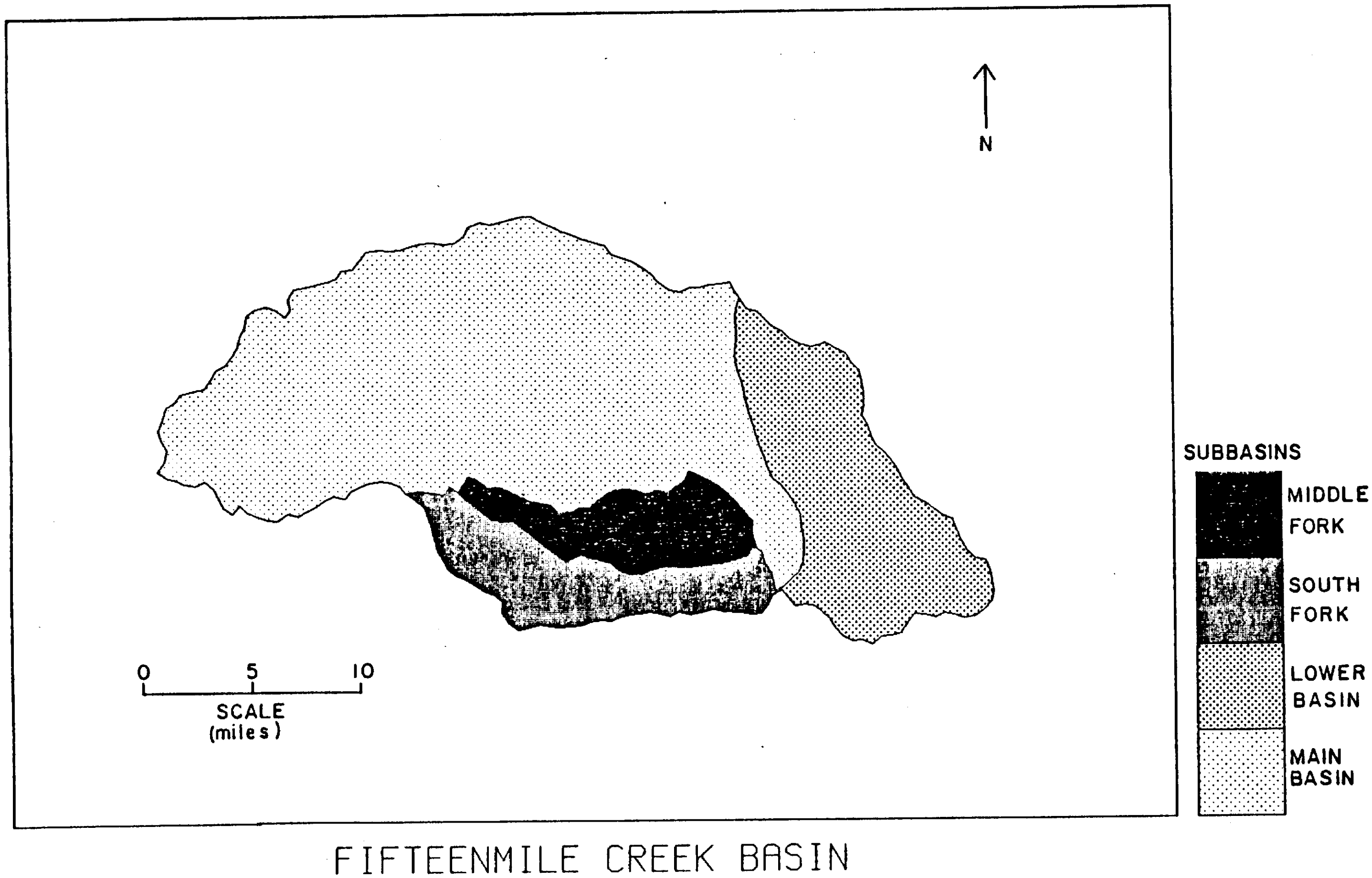


Figure 4. Fifteenmile Creek watershed and subbasins.

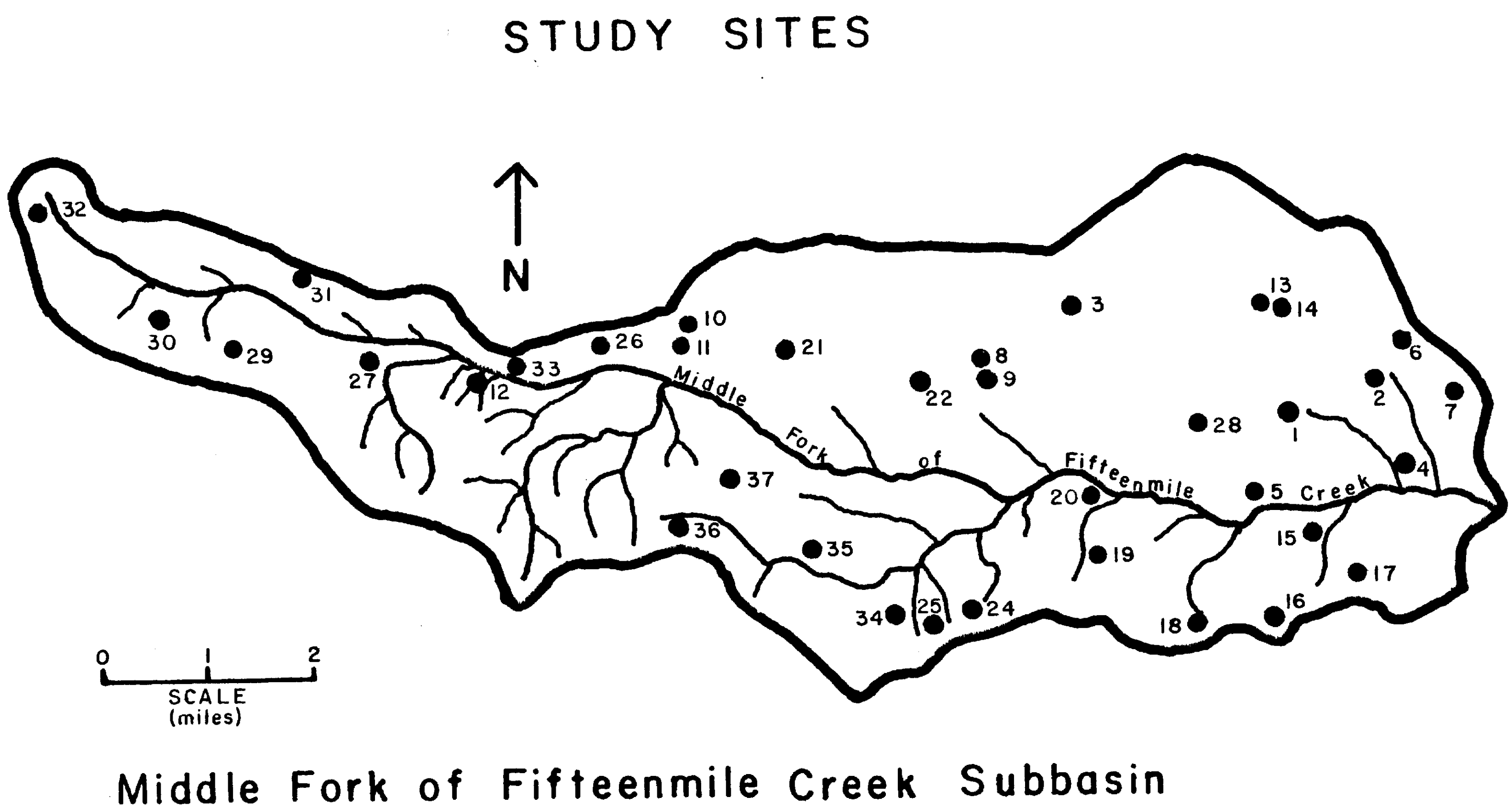


Figure 5. Location of rainfall simulation study sites in the Middle Fork subbasin.

sites (Figure 6). Water was transported in a 568 liter (150 gallon) polyethylene tank, which proved adequate for 12 experiments. Municipal water from the city of Worland, Wyoming was used in the study.

Once a site was selected, the simulator was set up and the plot prepared for an experiment. The simulator frame was placed over the plot and initially levelled with carpenter levels by raising or lowering the adjustable legs. The rainfall chamber was then placed on the frame followed by a plywood platform, water supply reservoir and flow meter using a stepladder. Setting up the simulator was completed with a final leveling of the apparatus. The plot boundary frame was then tapped into place and soil placed around the outside edges to ensure that no runoff escaped from the plot. The funnel trough was carefully tapped into place and a hole dug at the downslope end for the runoff collection containers as a final step.

The following parameters were recorded for each plot after setting up the simulator: vegetation density (visual estimate), vegetation type, vegetation frequency (direct count of number of plant stems), litter density (visual estimate), slope (measured with a (observation). clinometer), slope aspect (measured by compass), and antecedent moisture Photographs were taken of the site and each experimental plot. The location of the plot on the topographic map was then marked and recorded by section, township, and range. A surface soil sample was also collected at each site for later textural analysis.

With the preliminary work completed, the rainfall simulation was started. The sheet metal cover was first placed over the plot so it would not be disturbed while the drop formation was initially adjusted.

Figure 6. Truck, simulator, and water supply.

Once the cover was in place, water was allowed to flow unregulated into the rainfall chamber; this insured that the water had spread over the chamber and the tubes were all dripping adequately. The water was then routed through the flow meter and the meter adjusted so that the drops formed at the desired rainfall intensity.

The experiments were initiated by lifting the protective cover from the study plot and recording the start time. Runoff was funneled into a 500 ml (1 pint) sample bottle placed at the downslope end of the collection trough. Runoff samples were also taken at 15, 35, and 55 minutes during the 1-hour experiments; although when infiltration rates were high, all of the sample bottles were not used. The time the sample was taken and the time it took for the sample bottle to fill were recorded and the bottles appropriately labeled. Between samples, runoff was collected in a 4-liter (1-gallon) bucket, measured, and discarded. Water was pumped up into the supply reservoir and the flow meter adjusted periodically to insure a consistent rainfall intensity was maintained. Water that fell outside the plot boundary was collected in the gutter trough and funneled into a beaker with its volume noted. Any sediment that had collected in the funnel trough from rainsplash or deposition by surface runoff was washed into a container and labeled "splash sediment" for later analysis. The depth of infiltration was then measured by digging a hole into the plot with a trowel, and measuring the depth of wetted soil front.

Laboratory Data Analysis

Laboratory analysis of splash sediment, runoff and soil samples was performed in the Soils Laboratory at the Department of Geography and

Recreation at the University of Wyoming in the fall of 1987. Splash sediment, the amount of sediment deposited by either rainsplash or runoff in the collection trough at the downslope end of the plots, was measured by its dry weight (grams). Runoff samples were analyzed for volume (ml) by weight and sediment concentrations (mg/l) by evaporating the water and determining the weight of sediment in the sample. Soil samples were analyzed for particle size distributions (percent sand, coarse silt, fine silt, and clay) using the hydrometer method (Bouyoucos 1962).

The volume of water in each sample bottle and their filling times, recorded during the experiments, were used to calculate the total runoff (liters) from each plot. This was accomplished by calculating the discharge (volume/time) at each sample point, interpolating the discharge between points and, hence, the volume of runoff between samples. Finally, these values were added to estimate the total runoff from each study plot for the 1-hour simulated storm (Appendix A). This calculated volume was then compared to that measured in the field during the experiment.

The rates and volumes of runoff calculated and interpolation method used above, and the sediment concentrations of the samples (mg/l) were used to determine the total sediment (grams) carried off the plots. This amount of sediment was then added to the measured weight of splash sediment to calculate the total sediment eroded from the plot by the simulated rainstorm (Appendix A).

A method of defining soil texture numerically was chosen so the variables could be used in regression analysis. The percent sand, coarse silt, fine silt, and clay of the surface soil samples were determined and the particle sizes assigned the following numerical values:

1 = sand (0.5 - 2.0 mm)

2 = coarse silt (.005 - .05 mm)

3 = fine silt (.002 - .005 mm)

4 = clay (<.002 mm)

Soil texture for the sample was quantified by multiplying the percent of the sample in each size category by the assigned numerical value for the category, summing the four calculated values, and dividing this value by 100 (Appendix B). The resulting values for the samples fell between a 1 to 4 scale with 1 being coarse textured (sand) and 4 being fine textured (clay).

Meeuwig (1970) used the percent of the soil sample composed of particles greater than 0.5 mm as a way of defining soil coarseness for use in a regression equation for a similar research study. Since soils in the study area differed significantly from one another and were often very fine textured, the selected method was chosen as the best means of quantifying soil texture for this research.

Field visual estimates of vegetation density were verified by comparing these values to estimates of vegetation cover using the point-intercept method (Mueller-Dombois and Ellenberg 1974). Vertical photographs of 29 of the experimental plots were overlaid with a dot-grid to determine vegetative cover. A correlation between vegetation density values estimated by the visual and point-intercept methods was significant at $P < 0.001$ with an r^2 value of .89, slope (b) of .96, and intercept (a) of 0.004.

Computer Mapping

Both Bureau of Land Management site write-up area (SWA) maps and the slope maps created from U.S. Geological Survey topographic maps for the Middle Fork subbasin were digitized, line files edited, and polygon maps created using the University of Wyoming's Cyber 840 computer, a Tektronix digitizer and terminal, and FORTRAN programs written by Dr. Larry Ostresh of the Geography and Recreation Department at the University of Wyoming. The program GIN6 was used to digitize the maps onto the computer system. Because of the large size of the watershed and relatively small size of the digitizing tablet, it was necessary to break each of the two maps into seven pieces when digitizing. An editing program EDITGR3 was then used to combine the pieces into the final map and edit the digitized lines. Polygon maps were created from the digitized lines using the program POLYDG2. A separate data file was then created to assign values to the polygons.

Values assigned to the polygons of the slope map were the same as those originally delineated from the U.S. Geological Survey topographic maps. Vegetation densities for individual polygons of the Middle Fork SWA map were determined from range site descriptions included in the Soil Inventory of the Grass Creek Area, Wyoming (Knox et al. 1979) (Appendix C). Soil texture for the range sites was determined using soil texture descriptions from the Soil Inventory of the Grass Creek Area, and the Soil Survey of Washakie County, Wyoming (Iiams 1983), and soil texture data from the soil samples collected at the study sites (Appendix C). These data were then assigned to the polygons of a second SWA map data file to create the subbasin soils map.

The polygon slope and SWA maps and above calculated data were then used to create polygon maps of slope gradient, vegetation density, and soil texture in the Middle Fork subbasin. Plots and color slides of the polygon maps were made using the Versitec plotter and III FR80/A Computer Output to Microfilm (COM) Recorder at the Computer Services Center at the University of Wyoming and Dr. Ostresh's programs CMAPTN4 and PERSPC8, respectively.

Erosion and runoff maps were created for the watershed using two different procedures, both of which utilized Dr. Ostresh's programs. In the first method, polygon maps of erosion and runoff were created using data from the slope, vegetation and soils maps, and two regression equations. In the second procedure, matrix maps were generated from the three polygon maps. Regression equations were then used to combine the three maps and create matrix maps of erosion and runoff for the Middle Fork watershed.

In creating a polygon map of erosion and runoff, the slope map was used as a base map with portions of the soil and vegetation maps overlaid onto it using the digitizer, FORTRAN programs, and Tektronix terminal. Since polygons delineating soils and vegetation densities were often associated with the defined slope categories, this method appeared to be valid. Values for percent slope, vegetation density, and soil texture were then assigned to each of the 66 polygons which composed the final polygon map (Appendix D).

In the second procedure, matrix maps were constructed from the polygon maps for slope, vegetation density and soil texture, and their associated data files using the program POL2MAT. Three dimensional maps were created using the program PERSPC8 from these data. The final matrix maps for erosion and runoff were developed using regression equations and a program BLEND which combines matrix maps. Since the program blends only two matrices at a time, two steps through the program were necessary to blend the three matrices and create the final matrix maps.

Morphometric Analyses

Morphometric variables are quantitative expressions of the geometry of the drainage basin and stream network. A large literature exists supporting the use of morphometric variables in assessing differences between watersheds in runoff and sediment production (for example, see Marston 1978). Topographic maps (1:24,000, 7.5-minute series) were acquired for the entire Fifteenmile Creek watershed. The channel network was then delineated using the contour crenulation method. Specifically, the procedures are:

1. Draw channels from the lower end (mouth) upstream beginning where two or more consecutive contours have an angle of bend less than or equal to 120 degrees. To assist in this task, a template was prepared on a transparent overlay with the 120 degree angle shown.
2. Extend the channels upstream as long as at least one of every four contours has the critical angle of bend.
3. Draw the channel network through small lakes if any are present.

Morphometric measurements were performed for the entire Fifteenmile Creek watershed and each of the following sub-basins: South Fork, Middle Fork, Main Fork, and Lower Watershed (portion outside the other sub-basins). The morphometric variables measured are described in Tables 2-4.

RESULTS

Step-wise procedures were used to develop multiple linear regression equations identifying those variables that are the best predictors of surface runoff and soil loss by rainsplash and sheet erosion from the study sites. Variables tested in the two analyses were vegetation density (percent canopy cover), vegetation frequency (number of plants), litter density (percent ground cover), slope (percent), and soil texture (scale 1-4). The data used in the analysis are summarized in Appendix E. The regression equations predict soil loss (grams) and runoff (liters) produced from the .61 x .61 meter (2 x 2 foot) study plots by the 1-hour simulated rainstorms. Data from one of the study sites, site 31, were omitted from the regression procedures because the dense vegetation found on the slope, resulting from a spring or seep, was atypical of conditions in the watershed and its elimination resulted in a significant improvement in the regression equation. A simple linear regression was also developed to examine relationships between rates of erosion and runoff from the experimental plots. The generated multiple regression equations were then used along with computer digitized slope, vegetation, and soils maps of the Middle Fork subbasin to produce erosion and runoff maps for the watershed.

Sediment Production

Sediment production from the study plots can best be described by the equation:

Table 2. Derivation of morphometric variables that describe the watershed

Symbol	Variable	Derivation	Reference
A	Area of Basin	Direct measure	Horton 1945
BE	Basin Elongation	BE = (diameter of circle with same area as basin)/BL BE = $[2 \times (A/3.145)^{.5}]/BL$	Schumm 1956
BL	Basin Length	Direct measure of line extending through basin center to basin perimeter	Potter 1961
BR	Basin Relief	Direct measure of change in elevation along BL	Schumm 1956
BW	Basin Width	Direct measure along basin axis perpendicular to BL at basin center	Schumm 1956
C	Circularity	C = A/(area of circle with same P $C = A(4 \times 3.14 \times A)/P^2$	Miller 1953
CC	Compactness Coefficient	CC = P/(circumference of circle with same A)	Rothacher et al. 1967
FF1	Form Factor 1	$FF1 = A/BL^2$	Horton 1932
FF2	Form Factor 2	FF2 = BL/BW	Horton 1932
L	Lemniscate	$L = BL^2/(4 \times A)$	Chorley et al. 1957
P	Perimeter	Direct measure	Smith 1950
RER	Relative Relief	R = BR/(5280 x P)	Strahler 1964
RR	Relief Ratio	RR = BR/(5280 x BL)	Schumm 1956

Table 3. Derivation of morphometric variables that describe the channel network

Symbol	Variable	Derivation	Reference
B	Bifurcation Ratio	Antilog of absolute value of slope of regression of channel order versus log Nu	Strahler 1957
CLB	Ratio of SLR to B	CLB = CLR/B	Horton 1945
CLR	Channel Length Ratio	Antilog of absolute value of slope of regression of channel order versus log MLu	Horton 1945
CRR	Channel Relief Ratio	Antilog of absolute value of slope of regression of channel order versus log MRu	Horton 1945
CSR	Channel Slope Ratio	Antilog of absolute value of slope of regression of channel order versus log MSu	Horton 1945
ML	Mainchannel Length	Direct measure	Taylor and Schwarz 1952
MLu	Mean Length: uth Order Channels	MLu = (total length of uth order channels)/Nu	Horton 1945
MR	Mainchannel Relief	Direct measure	Taylor and Schwarz 1952
MRu	Mean Relief: uth Order Channels	MRu = (total relief of uth order channels)/Nu	Horton 1945
MS	Mainchannel Slope	MS = MR/(ML x 5280)	Taylor and Schwarz 1952
MSu	Mean Slope: uth Order Channels	MSu = MRu/(MLu x 5280)	Horton 1945
Nu	Number of uth Order Channels	Direct count	Strahler 1957

Table 3. (continued)

Symbol	Variable	Derivation	Reference
TE1	Transport Efficiency Factor 1	TE1 = B X TLC	Lustig 1965
TE2	Transport Efficiency Factor 2	TE2 = TNC x CSR	Lustig 1965
TLC	Total Length of Channels	Direct measure	Horton 1945
TNC	Total Number of Channels	Direct count	Horton 1945
TRC	Total Relief of Channels	Direct measure	Horton 1945

Table 4. Derivation of morphometric variables that describe the relationship of the channel network to the watershed

Symbol	Variable	Derivation	Reference
CCM	Constant of Channel Maintenance	CCM = 1/DD	Schumm 1956
CF	Channel Frequency	CF = TNC/A	Horton 1945
CPE	Concentration of Potential Energy	CPE = TRC/P	
DD	Drainage Density	DD = TLC/A	Horton 1945
LOF	Length of Overland Flow	LOF = 5280/(2 x DD)	Horton 1945
RD	Relative Density	$RD = CF/DD^2$	Strahler 1964
RN	Ruggedness Number	RN = (BR/5280) x DD	Melton 1958
TSP	Texture-Slope Product	TSP = DD x RR	Schumm 1969

$$\text{Log } \hat{Y} = 1.90 + 0.0340X_1 + -0.00916X_2 + 0.191X_3 \tag{3}$$

where: X_1 = slope gradient

X_2 = vegetation density

X_3 = soil texture

Table 5 summarizes the results of the regression procedure, with a correlation matrix of relationships between the variables presented in Table 6. Slope gradient, vegetation density, and soil texture as independent variables yielded the best regression equation for predicting soil erosion. Vegetation frequency and litter density did not contribute significantly to the predictive strength of the equation and were not included. The weight of soil eroded from the experimental plots was found to be related exponentially to the independent variables, therefore, the logarithm of grams of sediment was used as the dependent variable in the multiple regression analysis. A visual inspection of residual plots revealed that all relationships were essentially linear and the log transformation valid. Appendix F contains a residual plot of observed values versus those predicted by the final regression equation.

Slope gradient was found to be the single strongest predictor of erosion, being directly correlated with it and accounting for 62 percent of the variance in sediment loss from the experimental plots. Since the logarithm of soil loss was used as the dependent variable in the equation, it is apparent that as slopes steepen, soil losses increase significantly. Figure 7 illustrates the effect of slope on measured rates of erosion from two study plots. While the degree of vegetative and litter cover, and soil texture for the two sites were similar, sediment

Table 5. Regression summary table for erosion.

Variable	b	Beta Weight	r^2 (cumulative)	F^a
Y - Soil loss (grams)				
X_1 - Slope gradient	0.0340	0.520	0.623	117
X_2 - Vegetation density	-0.00916	-0.392	0.762	113
X_3 - Soil texture	0.191	0.195	0.792	89.8
Constant = 1.90				

N = 71

[a]These variables were all significant at the .001 level.

Table 6. Correlation matrices for erosion (r^2 values).

	Y	X_1	X_2	X_3
Y	1.0	0.629	-0.540	0.263
X_1	0.629	1.0	-0.276	0.118
X_2	-0.540	-0.274	1.0	-0.127
X_3	0.263	0.118	-0.127	1.0

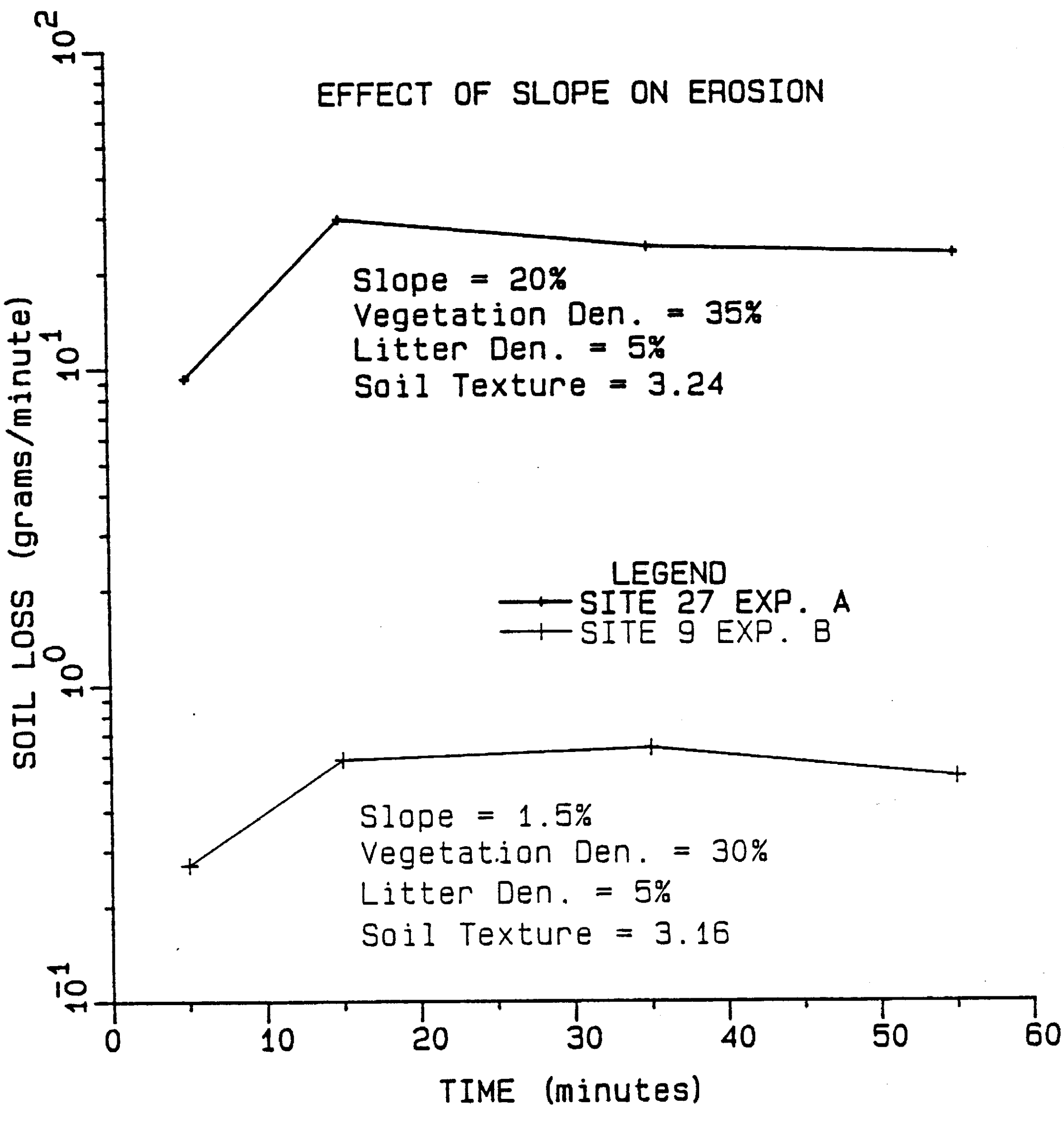


Figure 7. Effect of slope on rainsplash and sheet erosion.

production by site 27, with a slope of 20 percent, was substantially higher than that produced by site 9, where the slope gradient was 1.5 percent.

Vegetation density was found to be inversely correlated with erosion and the variable added significantly to the predictive strength of the multiple regression equation. Table 3 indicates that vegetation density alone can account for 54 percent of the variance in erosion from the study plots. The correlation matrix also shows litter density exerting strong control on erosion, however, the variable was not included in the equation due to its degree of multicollinearity with vegetation density. Figure 8 illustrates that as vegetation and litter densities increase, soil loss decreases markedly. Site 31, with 100 percent vegetative and litter cover, had far less soil loss than site 33, which had a similar slope gradient and soil properties but no litter or vegetative cover.

Soil texture was a moderate predictor of erosion, with the variable alone accounting for 26 percent of its variability (Table 3), and adding significantly to the predictive strength of the regression equation. As soil textures become finer, rates of erosion can be expected to increase. Figure 9 compares a site with fine textured soils, site 30, to one with coarse textured soils, site 8. Although slope gradient, and vegetation and litter densities were similar at the two sites, sediment production was found to be much higher at site 30 which has finer textured, clayey soils.

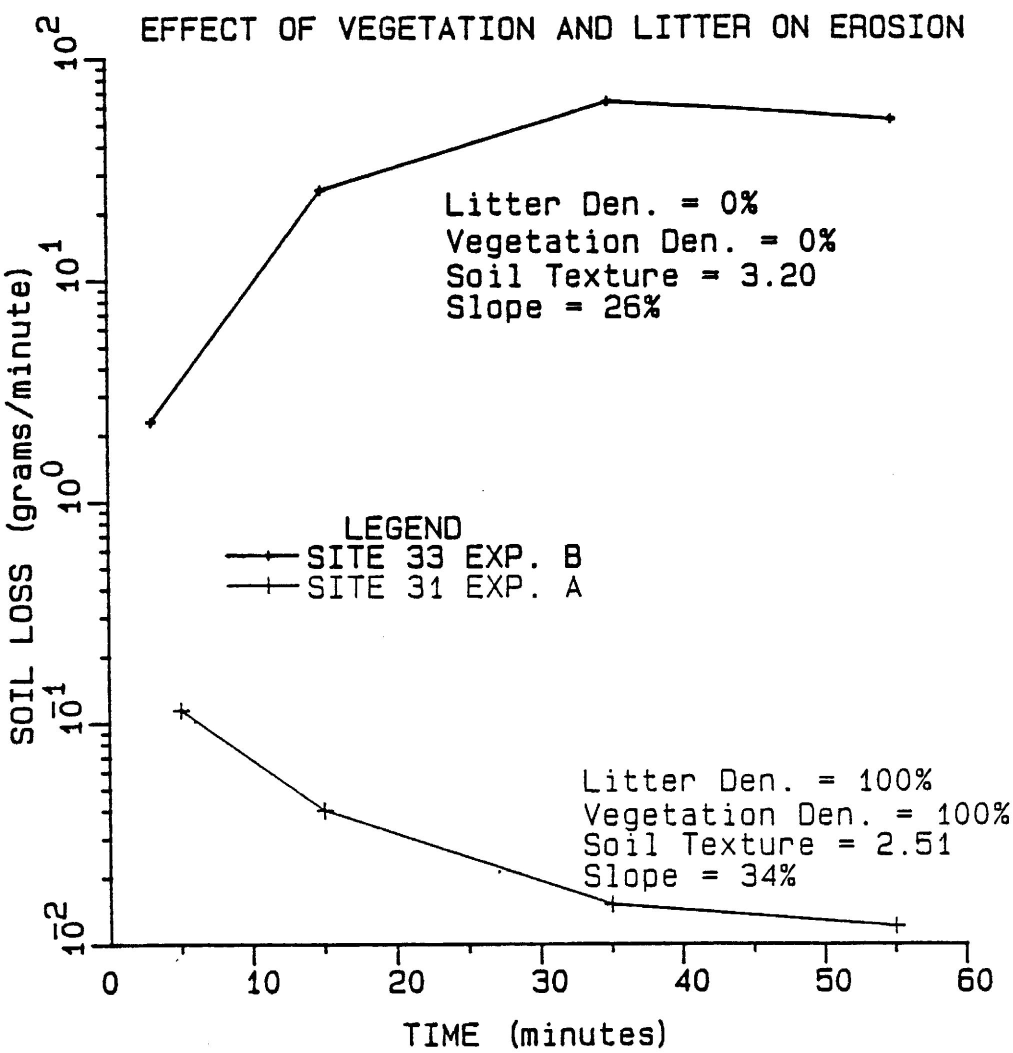


Figure 8. Effect of vegetation and litter on rainsplash and sheet erosion.

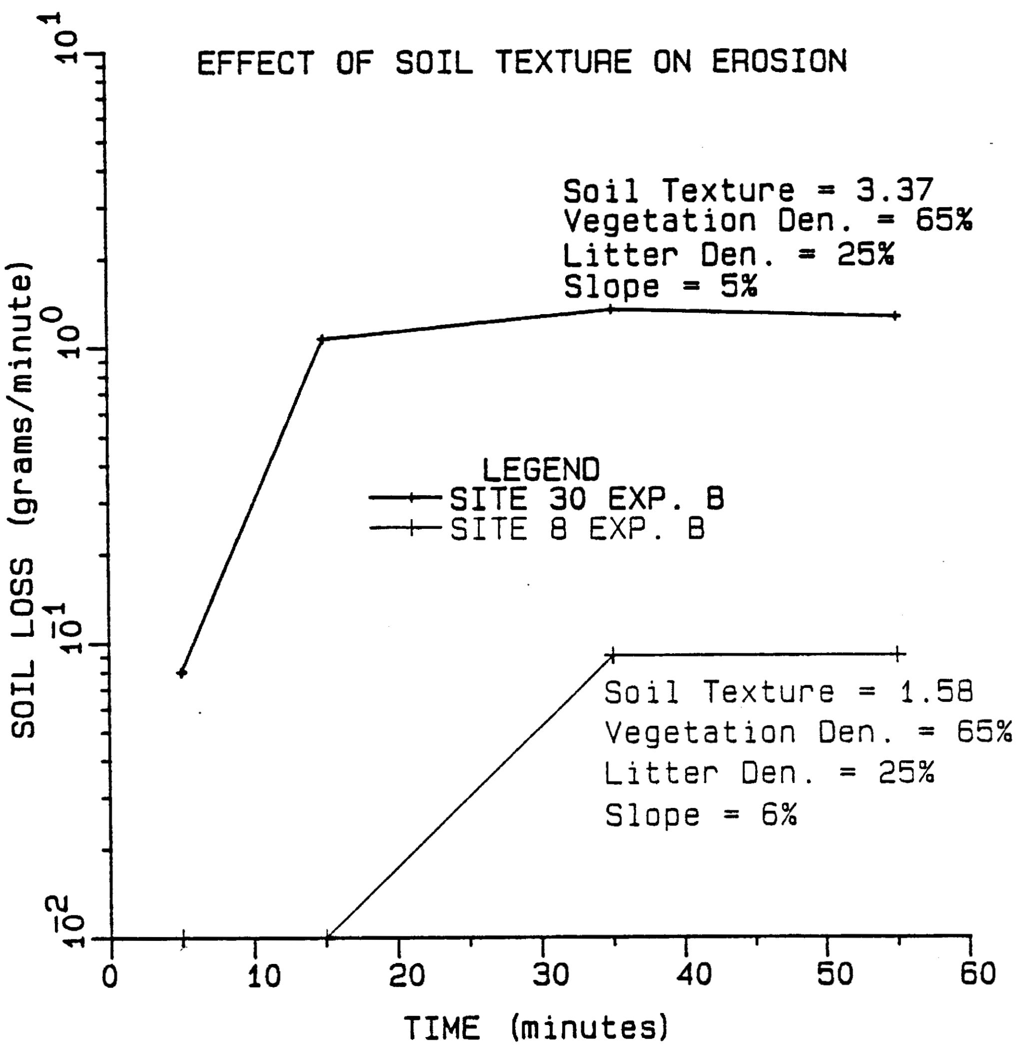


Figure 9. Effect of soil texture on rainsplash and sheet erosion.

Runoff

The equation found to best predict runoff (liters) from the study plots for the 1-hour simulated storms was:

$$\hat{Y} = 3.63 - 5.52(\text{Log}X_1) + 31.24(\text{Log}X_2) + 3.83(\text{Log}X_3) \qquad (4)$$

where: X_1 = litter density

X_2 = soil texture

X_3 = slope gradient

Tables 7 and 9 summarizes the results of the regression procedures and Table 8 illustrates a correlation matrix of all tested variables. Litter density, soil texture, and slope gradient were the predictors in the equation. Vegetation density and frequency did not contribute significantly to, and therefore were not included in, the equation. An evaluation of residual plots found the relationships to be essentially linear and the log transformations valid. A residual plot of observed values versus values estimated by the final equation is presented in Appendix F.

Table 7. Regression summary table for runoff.

Variable	b	Beta Weight	r (cumulative)	F[a]
Y - Runoff (liters)				
X_1 - Litter density	-5.52	-0.371	0.478	63.1
X_2 - Soil Texture	31.2	0.466	0.639	60.2
X_3 - Slope Gradient	3.84	0.234	0.670	48.4
Constant = 3.63				

N = 71

[a]These variables were all significant at the .001 level.

Table 8. Correlation matrices for runoff (r values).

	Y	X_1	X_2	X_3
Y	1.0	-0.477	0.466	0.218
X_1	-0.477	1.0	-0.229	-0.171
X_2	0.466	-0.229	1.0	0.029
X_3	0.218	-0.171	0.029	1.0

Table 9. Regression summary table for runoff using vegetation density in place of litter density.

Variable	b	Beta Weight	r (cumulative)	F^a
Y - Runoff (liters)				
X_1 - Soil Texture	35.7	0.532	0.459	60.5
X_2 - Vegetation Density	-0.0852	-0.293	0.593	52.1
X_3 - Slope Gradient	4.08	0.249	0.640	42.4
Constant = -0.972				

N = 71

[a]These variables were all significant at the .001 level.

Since no map data for litter density were available, a second regression equation which substitutes vegetation density for litter density was developed for use in the mapping portion of this research. The equation takes the form:

$$\hat{Y} = -.972 + 35.69(\mathrm{Log}X_1) + -.0852X_2 + 4.08(\mathrm{Log}X_3) \quad (5)$$

where: X_1 = soil texture

X_2 = vegetation density

X_3 = slope gradient

Tables 7 and 9 summarizes the results of the regression procedure and a residual plot of observed versus predicted values for runoff is presented in Appendix F. Soil texture, vegetation density, and slope gradient were the predictors in the equation.

Litter density was the strongest predictor of runoff from the study plots accounting for 48 percent of the variance. Vegetation density is also a strong indicator of runoff but was not included in the equation due to a strong degree of multicollinearity with litter density (Table 8). As litter and vegetative cover increase, runoff was found to decrease. Figure 10 illustrates the differences in runoff data from site 31, a site with 100 percent litter and vegetative cover, and site 33, having no litter or vegetative cover. Although slope gradient and soil textures were similar for the two sites, site 33 produced a substantially greater amount of runoff than site 31.

Soil texture was also found to be a strong indicator of runoff from the experimental plots. When used alone, the variable predicts 46 percent of the variability in runoff, and also adds significantly to the predictive strength of the multiple regression equation. Runoff is directly correlated with the soil texture index. Figure 11 illustrates that site 30, with a fine textured clayey soil, had high runoff production; while site 8, with a coarse textured sandy soil, had low runoff production. Slope gradient, and vegetation and litter densities were similar at the two sites.

The association between runoff and slope gradient was found to be moderate and positive with the variable adding significantly to the regression equation and alone accounting for 22 percent of the variability in runoff. Although runoff was found to be directly correlated

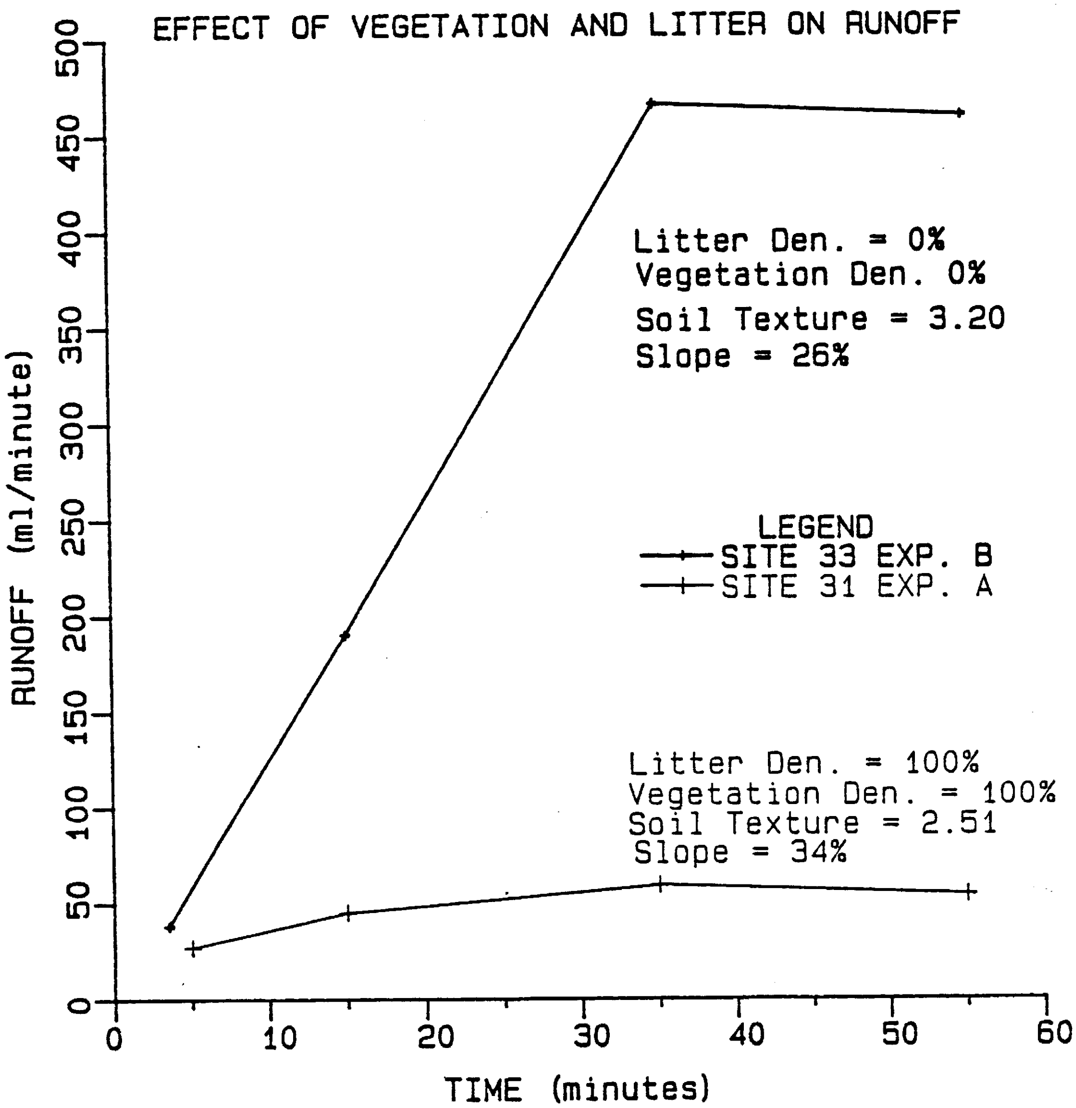


Figure 10. Effect of vegetation and litter on runoff production.

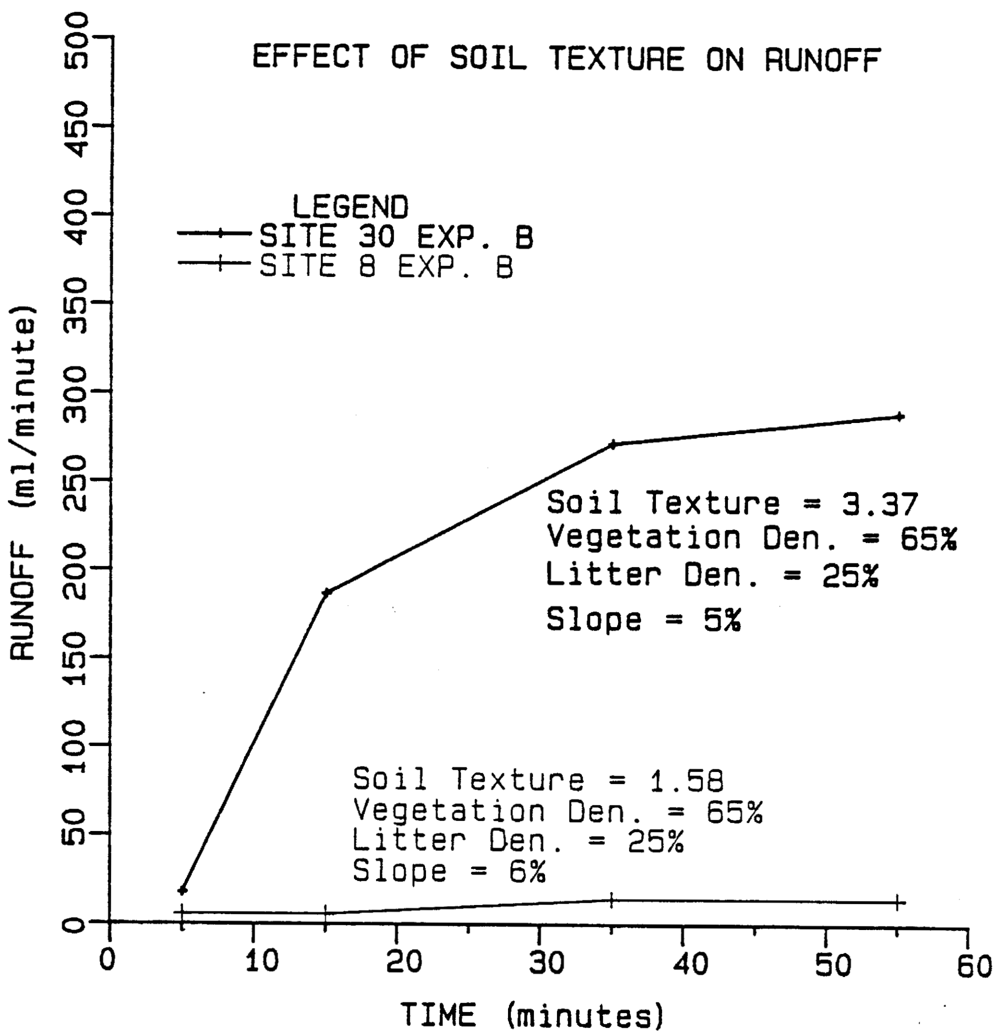


Figure 11. Effect of soil texture on runoff production.

with slope, Figure 12 illustrates that there are exceptions to the rule. The quantity and timing of runoff production by both sites 9 and 27 was similar even though the slope at site 27 was much steeper than that at site 9. vegetation densities, litter densities, and soil textures were similar at the two sites.

Correlation Between Runoff and Sediment Production

A regression equation was developed to examine the correlation between sediment production and runoff using erosion as the dependent variable. Although the correlation between the two variables was positive and highly significant p .001, the predictive strength of the regression equation was not extremely high $r^2 = 0.55$. The resulting regression equation takes the form:

$$\text{Log } Y = 1.59 + 0.0598X \tag{6}$$

where: $\hat{Y}$ = soil Loss (grams)

X = runoff (liters).

Results with the Modified Soil Loss Equation

The Universal Soil Loss Equation (USLE) developed by Wischmeier and Smith (1965) has been the most widely used model for estimating rates of land surface erosion. Originally developed for use on agricultural lands, the USLE has been modified for more general applicability by Warrington (1980). The Modified Soil Loss Equation (MSLE) takes the form:

$$A = R \times K \times L \times S \times (VM) \tag{7}$$

where: A = estimated soil loss per unit area

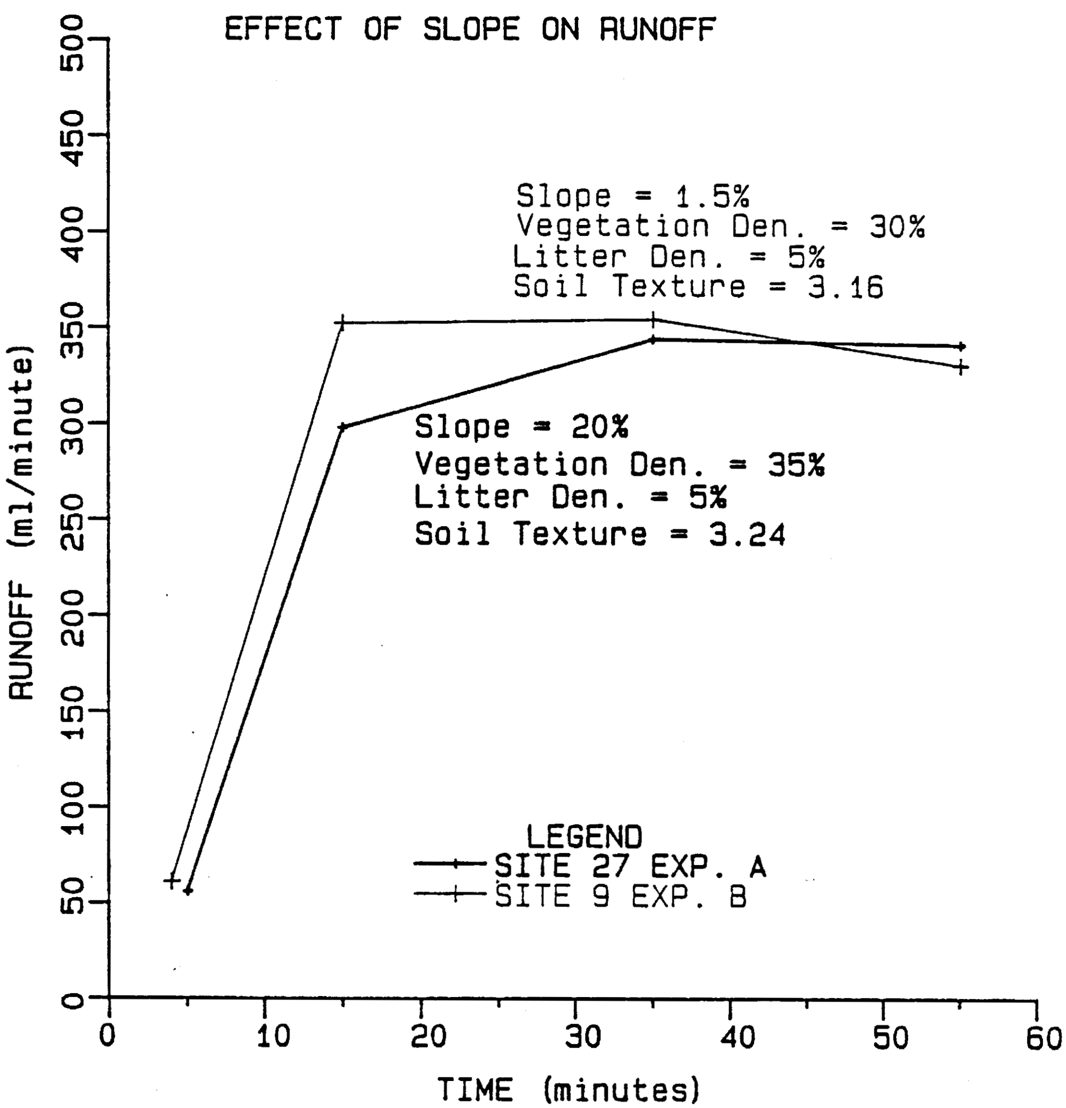


Figure 12. Effect of slope on runoff production.

R = rainfall factor

K = soil erodability factor

S = slope gradient factor

VM = vegetation management

The estimated soil loss with the MSLE was calculated for a storm of energy equivalent to the storm generated with the rainfall simulator. The value for R is calculated as follows:

$$R = (E \times I)/100 \tag{8}$$

where: E = total kinetic energy in foot-tons/acre-inch for a given storm

I = the storm intensity in inches/hour

With the rainfall simulator, E = 0.168 foot-tons over the plot for the 7.61 cm/h (3.0 inches/hour) storm, and I = 3.0 inches per hour. Therefore, R = 18.8 units, a constant value for all experiments. The values for K, L, S, and VM were derived using equations and nomograms published by Warrington (1980). Multiple regression was performed using the measured soil loss values for the dependent variable A, after a log transformation on the independent variables designed to produce a final equation similar in form to the MSLE. The resulting equation takes the form:

$$A = 1.22(LS)^{0.45}(k)^{-0.116}(VM)^{0.957} \tag{9}$$

where A is expressed in tonnes/hectare/hour. The R factor does not appear in the quation because it was held constant (i.e., it is incorporated in the constant value of 1.22. The r^2 value is 0.67, lower than achieved with Equation 3, but still significant at the p 0.001 level.

Note that the exponent values are not uniformly equal to 1.0 as has always been assumed in use of the USLE and MSLE. This exercise merely points out the shortcomings of using the MSLE without calibration to specific field areas.

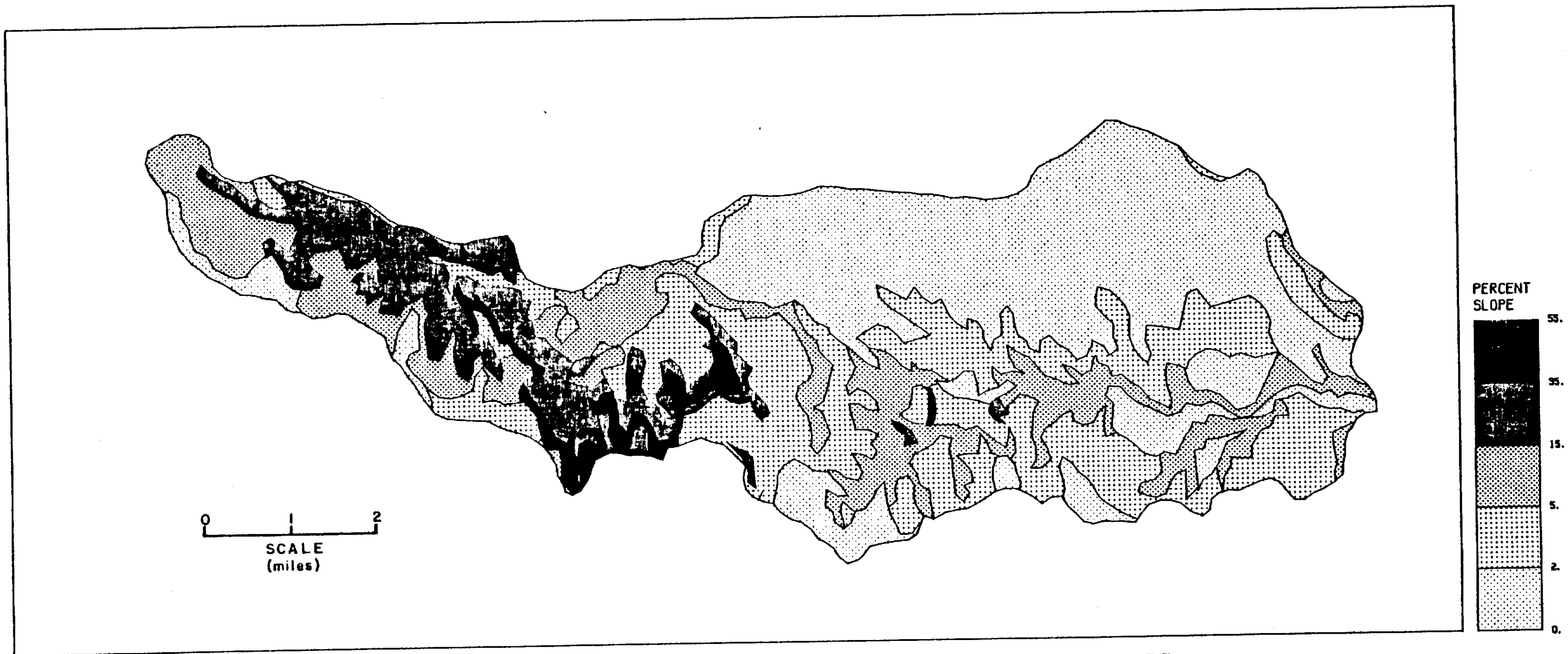
Computer Mapping

Base Maps

Figure 13 illustrates the watershed polygon slope map produced by the geographic information system. The areas of very steep slopes in the western portion of the watershed represent the basin badland areas. The extensive area of low slope in the northern portion of the basin is Dutch Nick Flat, an area of Quaternary alluvial deposits (Lowry et al. 1976). The more southern portions of the watershed contain flat upland areas, bluffs with steep to moderate slopes, flat lowlands, and areas of broken topography.

The polygon soils map for the Middle Fork subbasin (Figure 14) illustrates that finer textured clayey soils (texture 3-4) are associated with outcrops of the highly erodible Willwood formation (badland areas), mainly in the western portion of the basin. Coarser, sandy soils (texture 1-2) are usually found in flatter upland areas of the watershed, with loamy soils (texture 2-3) distributed in the remainder of the basin.

A computerized vegetation density polygon map (Figure 15) shows areas of high vegetative cover are generally found in association with low to moderate slopes and coarser textured soils. Areas of low vegetative cover are found in badland and saline upland areas of the watershed.

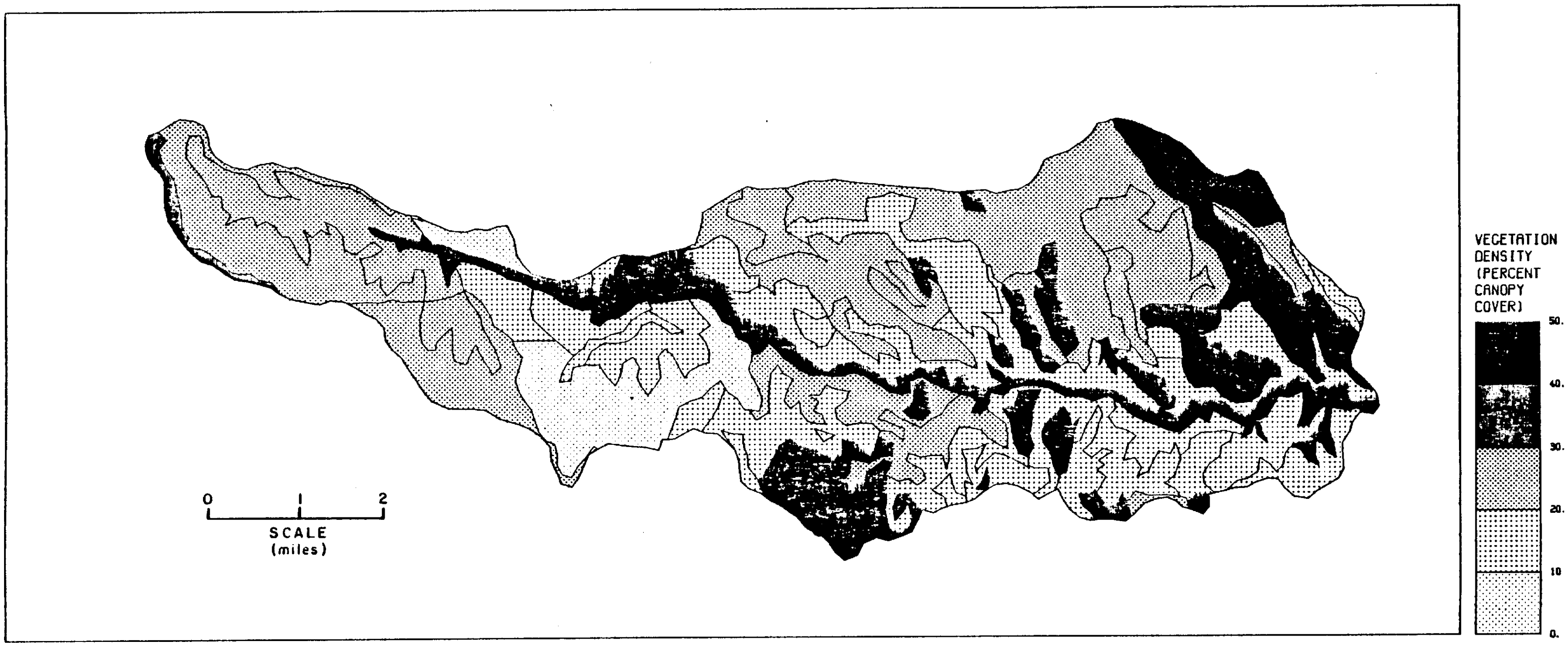


MIDDLE FORK OF FIFTEENMILE CREEK SUBBASIN - SLOPE MAP

Figure 13. Polygon slope map for the Middle Fork subbasin.

MIDDLE FORK OF FIFTEENMILE CREEK SUBBASIN - SOIL TEXTURE

Figure 14. Polygon soils map for the Middle Fork subbasin.



MIDDLE FORK OF FIFTEENMILE CREEK SUBBASIN - VEGETATION DENSITY

Figure 15. Polygon vegetation density map for the Middle Fork subbasin.

Erosion and Runoff Maps

The regression equations presented for erosion and runoff were used to reassign values to the elements of the final polygon map (Appendix D), thereby creating polygon maps that predict rates of erosion and runoff in the watershed. Figures 16 and 17 are the Versatec plots of the erosion and runoff maps created by these procedures. Erosion was converted to metric tons per hectare predicted to be produced by the 1-hour - 7.5 cm/hour simulated storms. Runoff was expressed as centimeters per hour produced by the experimental storms.

Versatec plots of matrix maps for slope gradient, vegetation density, and soil texture are presented in Figures 18, 19, and 20. These maps were created from their respective polygon maps and data files and are represented in the form of a 100 x 100 matrix grid. The matrix maps for erosion and runoff (Figures 21 and 22) were created by combining these matrices using the above presented regression equations.

In each of the matrix maps (Figures 18-22), a vertical exaggeration was used by the program PERSPC8 to produce the three-dimensional diagrams. The vertical dimension in these maps is measured in fundamentally different units than the horizontal dimensions with the vertical exaggeration being a ratio of these units. Vertical exaggerations for the maps were selected by trial and error to present the data in the best visual manner. While it is meaningful to compare heights of the variables in various locations on the same map, it is not meaningful to compare heights between different maps.

From the polygon and matrix maps, it is evident that rates of erosion vary significantly within the watershed. Highest rates of

MIDDLE FORK OF FIFTEENMILE CREEK SUBBASIN - EROSION

Figure 16. Polygon map of predicted rainsplash and sheet erosion for the Middle Fork subbasin.

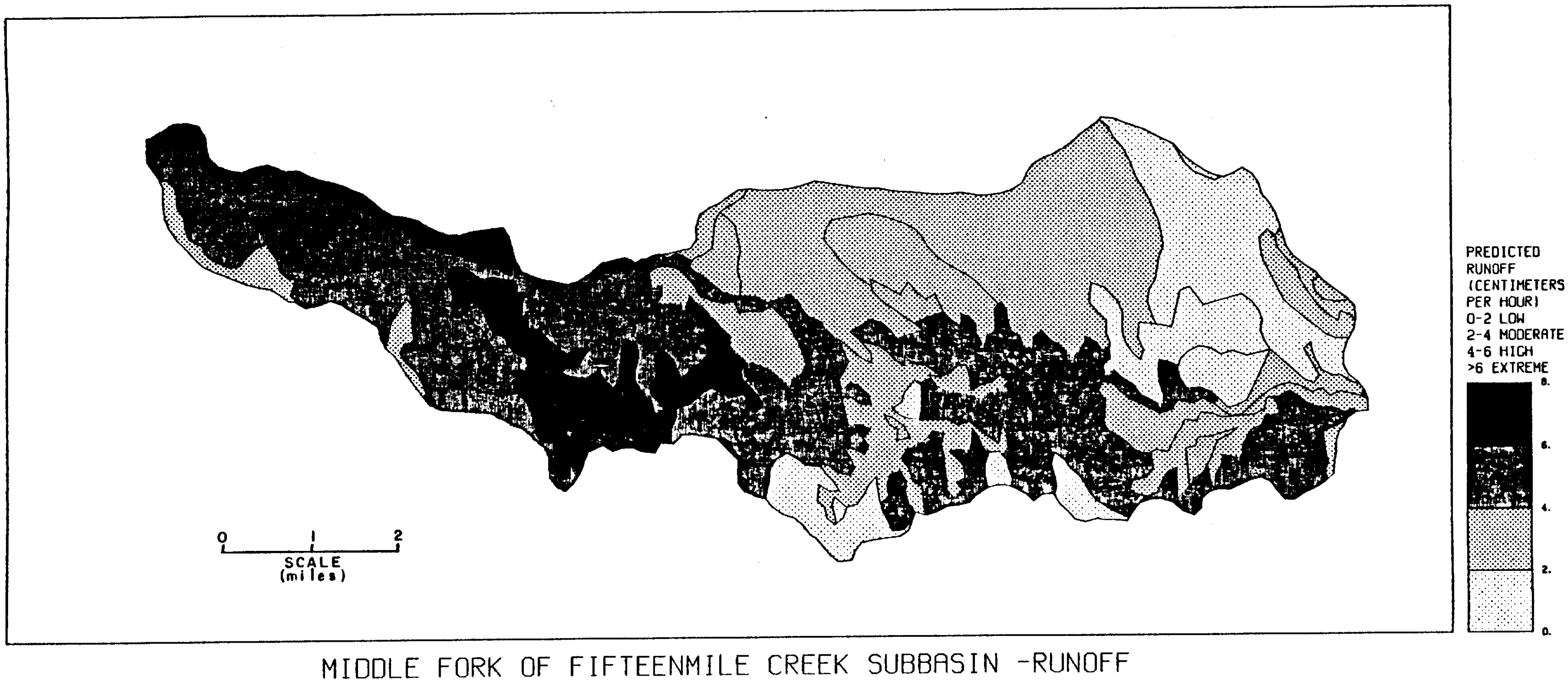
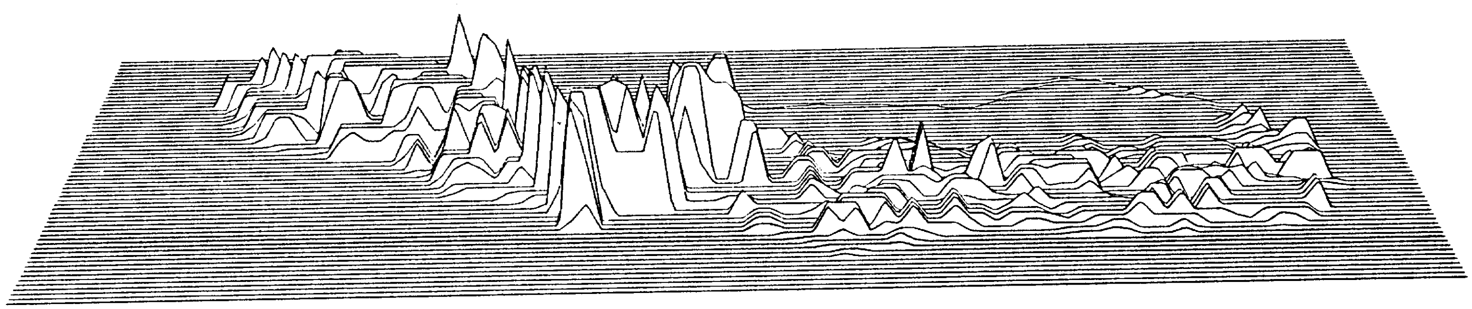


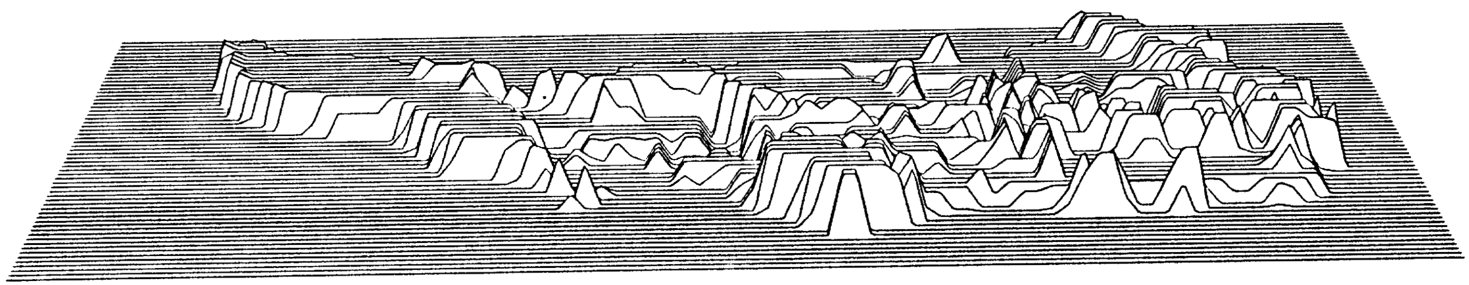
Figure 17. Polygon map of predicted runoff production for the Middle Fork subbasin.

Figure 18. Matrix slope map for the Middle Fork subbasin.



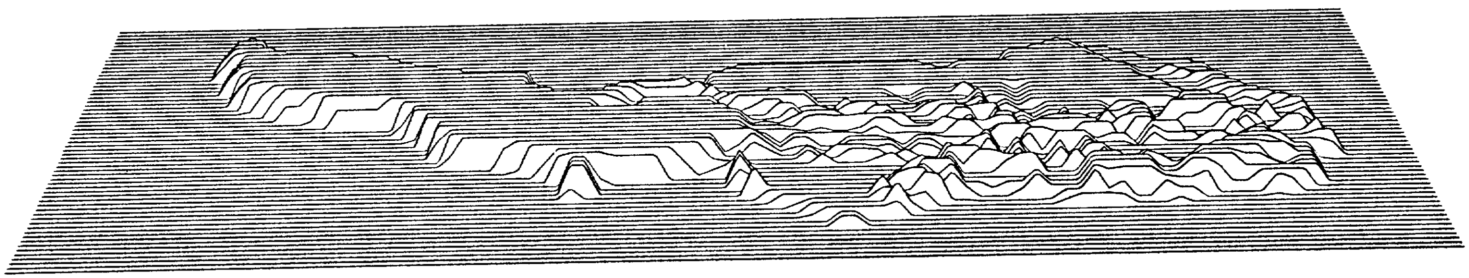
MIDDLE FORK OF FIFTEENMILE CREEK SUBBASIN - SLOPE

Figure 19. Matrix vegetation density map for the Middle Fork subbasin.



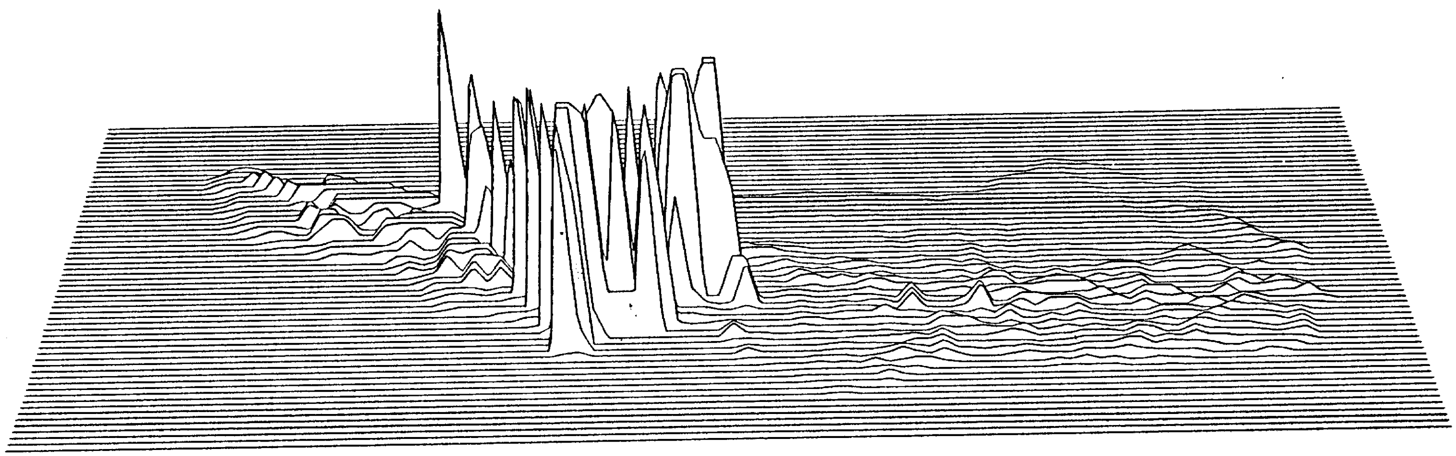
MIDDLE FORK OF FIFTEENMILE CREEK SUBBASIN - VEGETATION DENSITY

Figure 20. Matrix soil texture map for the Middle Fork subbasin.



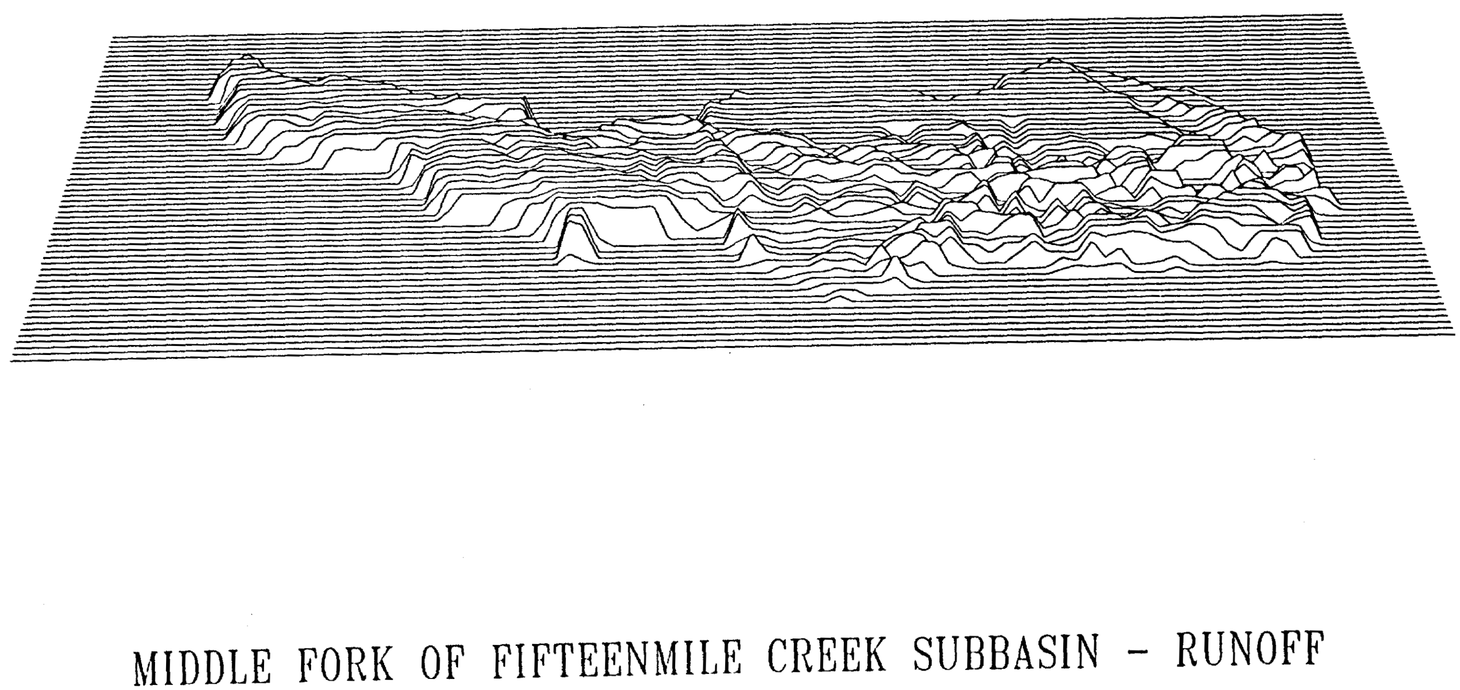
MIDDLE FORK OF FIFTEENMILE CREEK SUBBASIN - SOIL TEXTURE

Figure 21. Matrix map of predicted rain-splash and sheet erosion for the Middle Fork subbasin.



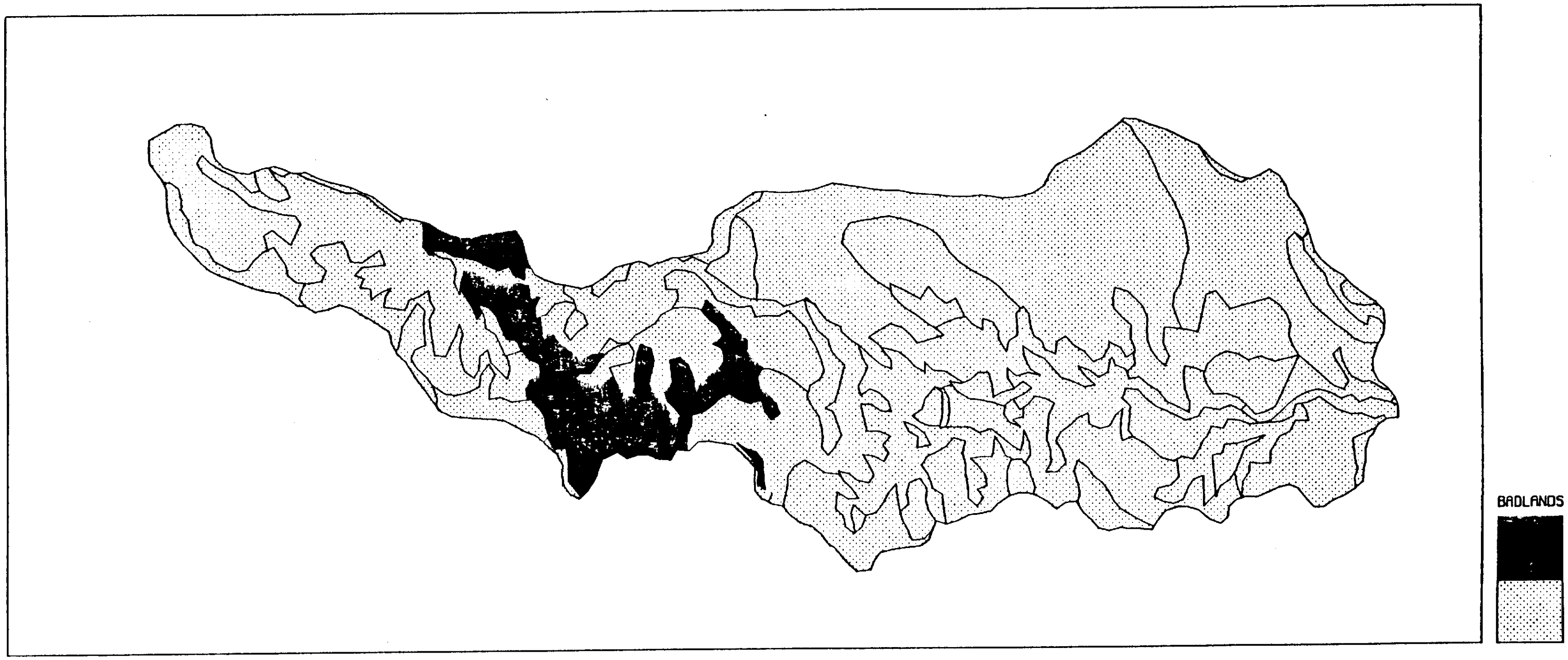
MIDDLE FORK OF FITEENMILE CREEK SUBBASIN - EROSION

Figure 22. Matrix map of predicted runoff production for the Middle Fork subbasin.



erosion are predicted in the badland areas of the western portion of the basin (Figure 23) and are a result of a combination of the steep slopes, low vegetation densities, and fine textured soils found in these zones. Comparatively low rates of erosion are found in areas of low slope, higher vegetation densities, and coarser textured soil. The Dutch Nick Flat area (Figure 24) characterizes zones of low erosion. Moderate rates of erosion are found in association with regions having moderate slopes and vegetation densities, and medium textured soils. The southern portions of the watershed are an example of the terrain type associated with moderate rates of erosion.

The relative contributions of the different terrain types found in the watershed to the total sediment budget of the basin was further examined using the polygon erosion map. This was accomplished by determining the area of each of the 66 polygons that make up the map using a FORTRAN program AREA written by Dr. Ostresh. These values, along with the erosion rates predicted for the polygons with the regression equation, were used to estimate the total soil loss for each polygon. The values are for gross erosion (not net delivery channels) predicted to be produced by an event similar to the 50-year storm. Table 7 summarizes the results of this procedure and the data used in the calculations are presented in Appendix G. The table illustrates that the badlands in the south-central portion of the basin (Figure 23), which make up only 8.47 percent of the total area of the watershed, account for 62.3 percent of the sediments predicted to be eroded by rainsplash and sheetwash. In contrast, the Dutch Nick Flat area (Figure 24) with 29.7 percent of the basin area accounts for only 5.51 percent



BADLAND AREAS

Figure 23. Badland areas in the Middle Fork subbasin.

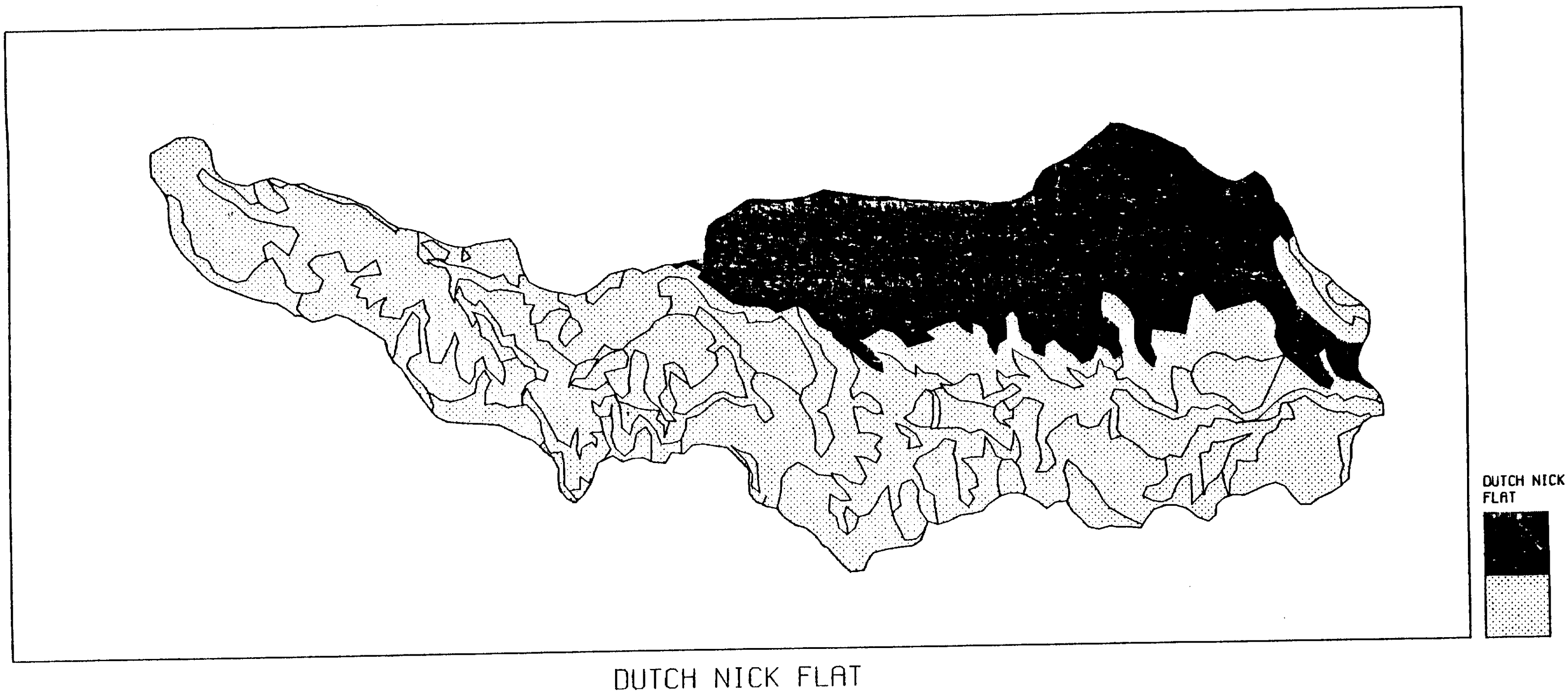


Figure 24. The Dutch Nick Flat area - Middle Fork subbasin.

of the predicted rainsplash and sheet erosion occurring in the watershed.

Predicted rates of runoff also exhibited marked variation within the watershed in response to different terrain types. The effect of soil texture on runoff is particularly evident from the runoff polygon and matrix maps (Figures 17 and 22). The western portions of the basin, with their fine textured soils, can be expected to have the highest rates of runoff. As with erosion, the badland areas are easily identifiable with their extreme rates of runoff. Moderate and low rates of runoff are found in association with coarser textured soils, low slopes, and high vegetation densities.

Morphometric Analyses

Values for the morphometric variables of Tables 2-4 are given in Tables 11-13. These values can be used in comparison of the slopes of regression equations for the Middle Fork, South Fork, and Main Fork of Fifteenmile Creek (Figure 25). Note that the sediment discharge per

Table 10. Estimated gross rates of rainsplash and sheet erosion for different terrain types in the watershed.

	Area (km)	Percent Total Area	Estimated Erosion (metric tons)	Percent of Total Erosion
Badlands	9.2	8.5	126000	62.4
Dutch Nick Flat	32.2	29.7	11100	5.5
Remainder of Watershed	67.3	61.8	64900	32.1
TOTALS	108.7	100.0	202000	100.0

Table 11. Values for morphometric variables that describe the watershed

Symbol	Units	South Fork	Middle Fork	Main Fork	Lower Wtsd.	Entire Wtsd.
A	mi^2	53.5	41.8	316	108	519
BE	---	.621	.507	.751	---	.669
BL	mi	13.3	14.4	26.7	---	38.4
BR	ft	1080	1240	1150	---	1610
BW	mi	3.56	4.29	13.9	---	18.5
C	---	.315	.338	.539	---	.549
CC	---	1.78	1.72	1.36	---	1.35
FF1	---	.302	.206	.443	---	.352
FF2	---	3.74	3.36	1.92	---	2.08
L	---	.827	1.24	5.64	---	.710
P	mi	46.2	39.4	85.8	50.7	109
RER	---	.00443	.00596	.00254	---	.00280
RR	---	.0154	.0160	.00816	---	.00793

unit of storm discharge is greatest for the Middle Fork subbasin and least for the Main Fork, with the South Fork curve attaining an intermediate slope. The morphometric variables that correlate with the slope of the three regression curves are (with direction of the correlation with the slope of the three regression curves are (with direction of the correlation indicated with a + or - symbol); A-, BE-, FF1-, L, P-, RER+, RR+, ML-, TLC-, TNC-, CF+, RD+, and TSP+. A physical rationale can be offered for the relationship between the slope of the regression curves and the morphometric variables, although too few curves exist for meaningful statistics to be performed. The larger the watershed area (and its surrogate variables P, ML, TLC, and TNC), and the lower the slope of the regression, because sediment delivery drops as watershed area increases. Variables that describe basin shape, BE, FF1 and L, demonstrate that more elongated basins produce less sediment. This is related to the timing of storm discharge from the basin perimeter. In

Table 12. Values for morphometric variables that describe the channel network

Symbol	Units	South Fork	Middle Fork	Main Fork	Lower Wtsd.	Entire Wtsd.
B	---	4.34	4.50	4.48	---	4.15
CLB	---	.551	.544	.545	---	.525
CLR	---	2.39	2.45	2.44	---	2.18
CRR	---	1.41	1.45	1.37	---	1.26
CSR	---	1.69	.590	1.78	---	1.73
ML	mi	23.9	17.8	57.5	---	77.3
ML1	mi	.147	.126	.148	.149	.146
ML2	mi	.231	.186	.235	.267	.237
ML3	mi	.597	.487	.566	.750	.597
ML4	mi	.866	.699	1.49	1.93	1.42
ML5	mi	1.83	3.26	3.07	4.13	3.09
ML6	mi	17.4	11.2	5.89	2.88	7.42
ML7	mi	---	---	40.3	3.37	21.8
ML8	mi	---	---	---	19.7	19.7
MR	ft	1680	1240	1530	---	1720
MR1	ft	86.8	79.2	86.3	59.6	80.4
MR2	ft	67.8	61.2	69.4	47.7	64.3
MR3	ft	85.7	69.0	90.4	78.1	85.7
MR4	ft	95.8	75.0	141	115	126
MR5	ft	127	347	185	158	186
MR6	ft	640	380	232	65	275
MR7	ft	---	---	580	80	330
MR8	ft	---	---	---	220	220
MS	---	.0133	.0132	.00503	---	.00422
MS1	---	.112	.119	.110	.0759	.105
MS2	---	.0556	.0625	.0558	.0338	.0514
MS3	---	.0272	.0268	.0302	.0197	.0272
MS4	---	.0209	.0203	.0179	.0113	.0168
MS5	---	.0131	.0202	.0114	.00725	.0114
MS6	---	.00696	.00642	.00746	.00428	.00702
MS7	---	---	---	.00272	.00449	.00287
MS8	---	---	---	---	.00212	.00212
N1	#	1618	1543	9194	3024	15379
N2	#	369	357	2126	672	3524
N3	#	89	69	470	140	768
N4	#	20	13	104	24	161
N5	#	5	3	27	6	41
N6	#	1	1	6	1	9
N7	#	---	---	1	1	2
N8	#	---	---	---	1	1
TE1	mi	1823	1428	10931	---	16683
TE2	#	3552	1172	21232	---	34401
TLC	mi	420	324	2440	831	4020
TNC	#	2102	1986	11928	3869	19885
TRC	mi	33.3	28.7	191	43.0	295

Table 13. Values for variables that describe the relationship of the channel network to the watershed

Symbol	Units	South Fork	Middle Fork	Main Fork	Lower Wtsd.	Entire Wtsd.
CCM	mi^2/mi	.127	.129	.130	.130	.129
CF	$\#/mi^2$	39.3	47.5	37.7	35.8	38.3
CPE	---	.721	.728	2.23	.848	2.71
DD	mi/mi^2	7.85	7.75	7.72	7.69	7.75
LOF	ft	336	341	342	343	341
RD	#/mi	.638	.791	.633	.605	.638
RN	---	1.61	1.82	1.68	---	2.36
TSP	mi/mi^2	.121	.124	.063	---	.0615

elongated basins, the runoff from distant parts of the watershed reaches the main channel with a great disparity in travel time whereas runoff from the perimeter of a circular basin tends to reach the mainstream at a similar time, causing larger peak flows (Gregory and Walling 1973). An increase in basin slope, expressed by either RER or RR, causes an increase in sediment production, confirming many other studies in the literature (Marston 1978). The positive relationship between CF and sediment production is quite normal; the greater the frequency of channels, the greater opportunity hillslope-derived sediment has to reach a channel and be exported from the basin. Similarly, the positive relationship between RD and the slope of regression curves means that a basin with a large number of short channels will produce more sediment than a basin with a low number of long channels.

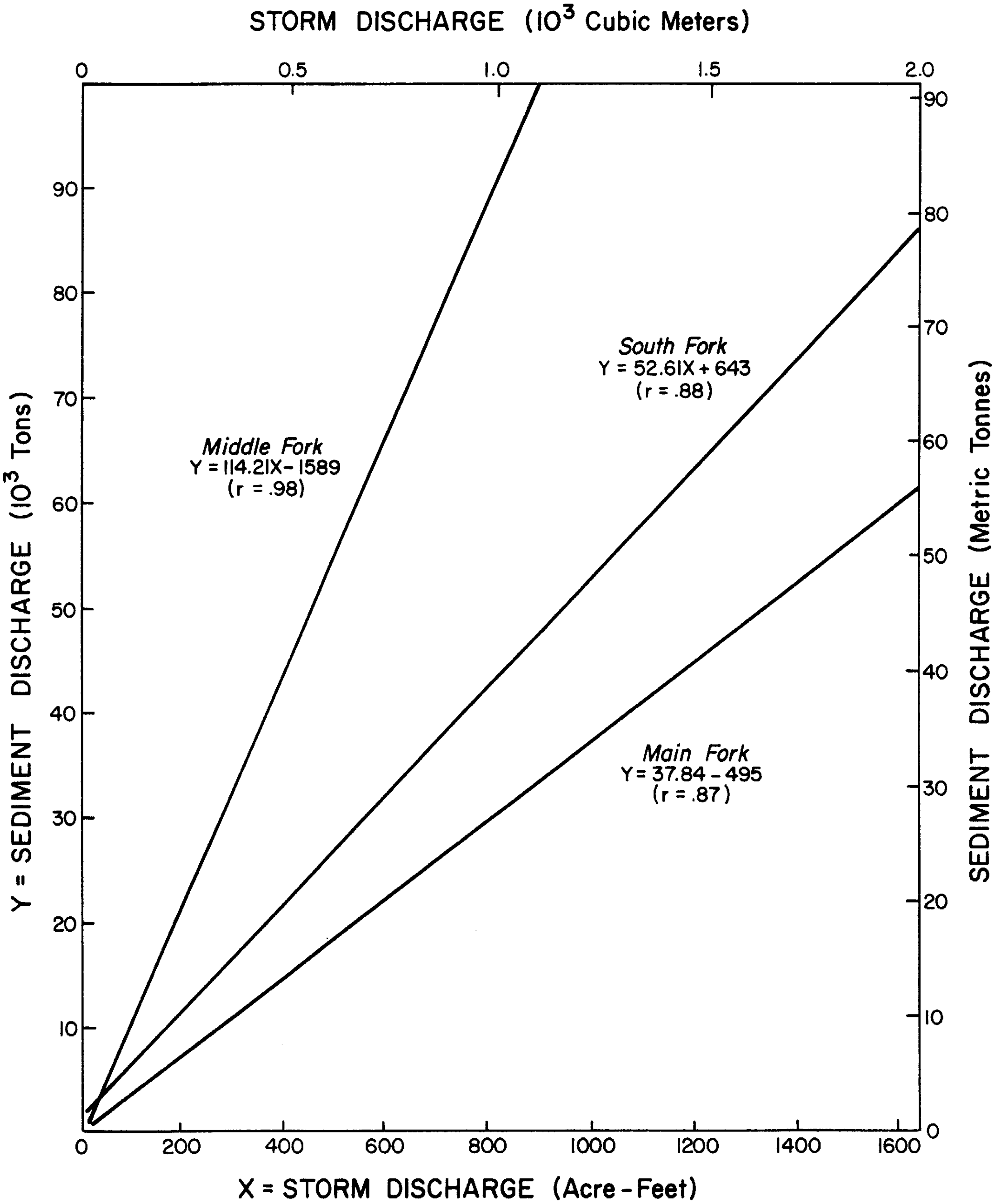


Figure 25. Regression of sediment discharge as a function of runoff for storm-period events in the Middle Fork, South Fork, and Main Fork subbasins. Source: Wilson (1973).

DISCUSSION

Erosion

The factors most important in determining rainsplash and sheet erosion in the Fifteenmile Creek watershed are slope gradient, vegetation density, litter density, and soil texture, with slope gradient exerting the strongest control. These same factors are also frequently cited in the literature addressing rainsplash and sheet erosion, although vegetative cover is often determined as being the most important variable (Branson et al. 1981). Meeuwig (1970) used plant and litter densities, air dry litter weight, soil organic matter content, and slope gradient to predict soil erosion on rangelands in Utah using rainfall simulation and regression analysis.

The downslope movement of soil particles detached by the impact of falling raindrops is greatest on steep slopes. Also, as slope gradient increases, so will the velocity of surface runoff, resulting in more kinetic energy available for erosion by sheetflow. Steep slopes in the watershed also typically have low amounts of vegetative and litter cover, and fine textured soils, making them even more susceptible to erosive forces. The badland areas with their extremely steep slopes, lack of vegetative and litter cover, and clayey soils are an example of these associations.

Vegetative cover serves to protect the soil surface by both shielding it from the direct impact of falling raindrops, and by intercepting and slowing the velocity of the falling drops. Vegetative cover also decreases the velocity of, and protects the soil surface from, the erosive forces of overland flow. Litter, which is strongly associated with vegetative cover, provides a similar protection of the soil surface. Areas of high vegetation and litter densities in the basin were often found in association with coarser textured soils, low slope gradients and hence areas of low sediment production.

Fine textured soils such as the clayey soils found in much of the western portion of the watershed were found to be easily dispersed by rainsplash and sheetwash. Coarser sandy soils were found to be less susceptible to erosion and in addition were associated with low slope gradients and good vegetative cover.

The rates of erosion and relative contributions of different terrain types estimated by this research are not absolute, however, they appear consistent with the results of previous research. Applying 6.3 centimeters (2.5 inches) of simulated rainfall, Meeuwig (1970) measured soil erosion rates ranging from .005 to 56 metric tons per hectare for rangelands in northern Utah. Bryan and Campbell (1980) estimated erosion rates as high as 47.5 metric tons per hectare in the Steville badlands in the Red Deer River watershed of Alberta using a study plot subject to 13.8 centimeters (5.4 inches) of natural rainfall over a three month period. Campbell (1977) found badlands occupy only two percent of the Red Deer River drainage basin, but contribute 80 percent of the total suspended sediment load.

The gross rainsplash and sheet erosion estimated by this research for the entire Middle Fork watershed from an event similar to the 50-year storm is 202,000 metric tons. This value does not appear unrealistic when compared to the 47,000 metric ton sediment discharge measured near the mouth of the stream by Wilson (1983) which resulted from a precipitation event that produced only 1.13 centimeters (.446 inches) of runoff. It is important to note that much of the sediment eroded by rainsplash and sheet flow will be redeposited and often never reaches a stream channel. However, the contributions of other types of erosion such as piping, rilling, and gullying were not quantified in this research.

The differences in sediment production between various subbasins of the Fifteenmile Creek watershed can be explained in a qualitative sense by several morphometric variables. However, a more quantitative analysis could be accomplished by mapping terrain types in subbasins other that the Middle Fork and by collecting more storm period sediment data similar to those of Wilson (1973). Then it would be possible to combine estimates of gross erosion rates (derived by the models in this study) with the morphometric variables which help to describe sediment deliverly.

Runoff

Areas of the watershed that are susceptible to erosion are also likely to produce high rates of runoff. As with erosion, the badland areas were found to produce the greatest amounts of surface runoff while areas of lower runoff production, such as the Dutch Nick Flat area, also have low rates of sediment yield. Despite the geographical similarities, the relationship between sediment production and runoff was not found to be exceptionally strong. This is possibly due to the protection of the soil surface from the impact of falling raindrops provided by ponded water and/or sheet flow.

The presence of vegetation and litter decreases rates of runoff by intercepting the falling raindrops and absorbing water on the soil surface. Plants also have a positive effect on soil structure resulting in higher rates of infiltration and decreased runoff. In addition, opportunities for depression storage were often observed in association with plant communities. This was found to be particularly true in blue grama and prickly pear cactus plant communities.

Coarser textured sandy soils are more permeable and therefore exhibit greater infiltration potential then finer textured clayey soils which, although porous, can exhibit hydrophobic characteristics. The western portions of the basin, with their fine textured soils, were found to have greater runoff production potential than the more coarsely textured soils that are found in much of the eastern portion of the watershed.

Greater amounts of runoff were also found to be associated with steeper slopes. This is likely due to lessened opportunities for depression storage, and greater surface runoff velocities. As is the case with erosion, it is important to note the associations between the predictor variables when determining their relative influence on runoff.

Evaluation of the Big Horn Basin Rainfall Simulator

Advantages of the rainfall simulator used in this research are that representative runoff and sediment production data can be collected quickly, in areas where access is limited, and at minimal expense. The simulator can be set up and the plot prepared for an experiment by two people in 30 minutes. Also, the simulator is portable and has comparatively low water consumption with the unit, necessary equipment and water supply easily transported in a standard pick-up truck. The usefulness of the simulator is further strengthened by the high degree of significance that was found during the statistical analysis of the data collected by this research. However, due to the small size of the study plots, the values predicted for rainsplash and sheet erosion, and runoff production by this research are not absolute but are useful in comparing relative rates of sediment and runoff production by different terrain types in the watershed. The data are also useful in identifying and quantifying the relative importance of those variables which control sediment and runoff production in the basin.

The Big Horn Basin rainfall simulator would be useful in other research projects, especially those which examine watershed sediment budgets. However, an improvement in experimental design suggested from observations made during this study would help to provide better data for future research projects.

Although no improvements are suggested for the rainfall simulator, improving the methods used to estimate slope gradient could serve to quantify this variable more accurately. Slope gradient was measured for all the study sites by use of a clinometer. On the final four study sites, a pantometer was also used to measure slope and these values for slope gradient varied from those measured by the clinometer. The pantometer, which measures the micro slope, would possibly provide better information on the slope gradient of small experimental plots such as those used in this research than the clinometer, which measures the gradient of a longer slope.

CONCLUSIONS

This project has employed field data collection, statistical analysis, and computer mapping techniques to identify those variables most important in determining runoff, and rainsplash and sheet erosion in the Middle Fork of Fifteenmile Creek watershed and to define sources of sediment and runoff in the drainage basin. In summary, the conclusions of this research are:

1. The factors most important in determining erosion and runoff from upland areas of the watershed are vegetative and litter cover, slope gradient, and soil texture.
2. Rates of erosion vary significantly within the watershed in response to terrain type, with badlands accounting for a disproportionately high percentage of the upland sediment production.

Agencies can choose to address sediment production in the Fifteenmile Creek watershed using either structural or nonstructural measures or can elect to initiate no new sediment control measures. Possible implications and limitations of these strategies are:

1. If agencies elect to pursue non-structural measures for reducting sediment production, then those measures will be limited to areas of the watershed where vegetation densities can be improved or new vegetation established. It is unlikely that vegetative cover could be improved or established in the areas of the watershed having the highest sediment production potential.
2. If agencies elect to pursue structural controls on sediment production, then structures would be most effective if constructed adjacent to badland areas. However, the effective life of sediment control structures adjacent to these areas is likely to be short. Periodic maintenance of the structures would also be needed. A comprehensive inventory of the

condition, efficiency, and expected operational life of existing structures in the basin would help to clarify the past effectiveness of these types of erosion control measures.

3. If agencies elect to pursue no further sediment control measures in the watershed, then sediment production by the watershed will remain high and downstream water users will need to continue to manage for negative effects created by the sediments. These effects include increased costs for municipal water treatment, damage to fisheries, and reduced storage volume in Yellowtail Reservoir.

LITERATURE CITED

Barnett, A.P. and A.E. Dooley. 1972. Erosion potential of natural and simulated rainfall compared. American Society of Agricultural Engineers, Transactions 15:1112-1114.

Blackburn, W.H., R.O. Meeuwig and C.M. Skau. 1974. A mobile infiltrometer for use on rangeland. Journal of Range Management 27:322-323.

Blackburn, W.H. and C.M. Skau. 1974. Infiltration rates and sediment production of selected plant communities in Nevada. Journal of Range Management 27:476-480.

Bouyoucos, G.J. 1962. Hydrometer method improved for making particle size analysis of soil. Agronomy Journal 54:464-465.

Branson, F.A., G.F. Gifford, K.G. Renard, and R.F. Hadley. 1981. Rangeland Hydrology. Dubuque, Iowa: Kendall-Hunt.

Bryan, R.B. and I.A. Campbell. 1980. Sediment entrainment and transport during local rainstorms in the Steveville Badlands, Alberta. Catena 7:51-65.

Bryan, R.B. and W.K. Hodges. 1981. Runoff and sediment transport dynamics in Canadian badland micro-catchments. In Catchment Experiments in Fluvial Geomorphology, ed. T.P. Burt and D.E. Walling, pp. 115-131. Cambridge: Exeter and Huddersfield.

Bubenzer, G.B. and B.A. Jones. 1971. Drop size and impact velocity on the detachment of soils under simulated rainfall. American Society of Agricultural Engineers, Transactions 14:625-628.

Bubenzer, G.B., M. Molnau, and D.K. McCool. 1979. Palouse rainfall simulator. In Proceedings of a Rainfall Simulator Workshop, pp. 131-133. Tucson, Arizona: U.S. Department of Agriculture, ARM-W-10.

Campbell, I.A. 1977. Stream discharge, suspended sediment and erosion rates in the Red Deer River basin, Alberta, Canada. International Association of Hydrological Sciences Publication 122:244-259.

Chorley, R.J., D.E.G. Maim and H.A. Pogorzelski. 1957. A new standard for estimating basin shape. American Journal of Science 255:138-141.

Chow, V.T. and T.E. Harbough. 1965. Raindrop production for laboratory watershed experimentation. Journal of Geophysical Research 70:6111-6119.

Cooper, C. 1979. 208 Water quality management plan for the Bighorn Basin, Wyoming. Regional Planning Office, Basin, Wyoming.

Dorn, R.D. 1986. The Wyoming Landscape, 1805-1878. Cheyenne, Wyoming: Mountain West Publishing.

Dortignac, E.J. 1951. Design and operation of the Rocky Mountain infiltrometer. U.S. Forest Service, Rocky Mountain Forest and Range Experiment Station, Paper Number 5.

Foster, G.R., F.P. Eppert, and L.D. Meyer. 1979. A programmable rainfall simulator for field plots. In Proceedings of a Rainfall Simulator Workshop, pp. 45-59. Tucson, Arizona: U.S. Department of Agriculture, ARM-W-10.

Gilliland, M.W. and W. Baxter-Potter. 1987. A geographic information system to predict non-point source pollution potential. Water Resources Bulletin 23:281-291.

Gregory, K.J. and D.E. Walling. 1973. Drainage Basin Form and Process. London: Edward Arnold.

Horton, R.E. 1932. Drainage basin characteristics. American Geophysical Union Transactions 13:350-361.

Horton, R.E. 1945. Erosional development of streams and their drainage basins; hydrophysical approach to quantitative morphology. Geological Society of America Bulletin 56:275-370.

Iiams, J.E. 1983. Soil Survey of Washakie County, Wyoming. U.S. Department of Agriculture, Soil Conservation Service.

Imenson, A.C. 1983. Studies of erosion thresholds in semi-arid areas: field measurements of soil loss and infiltration in northern Morocco. In Rainfall Simulation, Runoff and Soil Erosion, ed. J. de Ploey, pp. 80-89. Braunschweig, West Germany: Catena Supplement 4.

Johnson, A. 1962. Effects of grazing intensity and cover on the water intake rate of fescue grassland. Journal of Range Management 15:79-82.

Knox, E.G., E.C. Nielson, and R.F. Wells. 1979. Soil inventory of the Grass Creek area Wyoming. Columbia, MD: Soil and Land Use Technology, Inc.

Laws, J.O. 1941. Measurement of the fall velocity of waterdrops and raindrops. American Geophysical Union, Transactions 22:709-721.

Laws, J.O. and A.P. Parsons. 1943. The relation of raindrop-size to intensity. American Geophysical Union, Transactions 2:452-460.

Lowry, M.E., H.W. Lowham, and G.C. Lines. 1976. Water Resources of the Bighorn Basin, Northwestern Wyoming. U.S. Geological Survey Atlas HA-512.

Lusby, G.C. 1970. Hydrologic and biotic effects of grazing vs. non-grazing near Grand Junction, Colorado. Journal of Range Management 23:256-260.

Lustig, L.K. 1965. Sediment yield of the Castaic watershed, west Los Angeles County, California, a quantitative geomorphic approach. U.S. Geological Survey Professional Paper 442-F.

Marsh, W.M. 1983. Landscape Planning: Environmental Applications. Reading, MA: Addison-Wesley.

Marston, R.A. 1978. Morphometric indices of streamflow and sediment yield from mountain watersheds in western Oregon. U.S. Forest Service Research Project 00-04T0-9-73, Corvallis, Oregon.

Martner, B.E. 1987. Wyoming Climate Atlas. Lincoln, NE: University of Nebraska Press.

Meeuwig, R.O. 1970. Infiltration and soil erosion as influenced by vegetation and soil in Northern Utah. Journal of Range Management 23:185-188.

Melton, M.A. 1958. Correlation structure of morphometric properties of drainage systems and their controlling agents. Journal of Geology 66:442-460.

Meyer, L.D. 1979. Methods for attaining desired rainfall characteristics in rainfall simulators. In Proceedings of a Rainfall Simulator Workshop, pp. 35-44. Tucson, Arizona: U.S. Department of Agriculture, ARM-W-10.

Meyer, L.D. and D.L. McCune. 1958. Rainfall simulator for runoff plots. Agricultural Engineering 29:644-648.

Miller, V.C. 1953. A quantitative geomorphic study of drainge basin characteristics in the Clinch Mountain area, Virginia and Tennessee. Office of Naval Research Project NR 389-042, Tech. Rept. 3, Columbia University.

Monmonier, M.S. 1982. Computer Assisted Cartography. Englewood Cliffs, N.J.: Prentice-Hall.

Mueller-Dombois, D. and H. Ellenberg. 1974. Aims and Methods of Vegetation Ecology. New York: John Wiley and Sons.

Mulkey, L.A. 1980. An approach to water resources evaluation of non-point silvicultural sources: a procedural handbook. U.S. Environmental Protection Agency Report 600/8-80-012, Athens, GA.

Munn, J.R. and G.L. Huntington. 1976. A portable rainfall simulator for erodibility and infiltration measurements on rugged terrain. Soil Science Society of America Journal 40:622-624.

Novotny, V. and G. Chesters. 1981. Handbook of Nonpoint Pollution. New York: Van Nostrand Reinhold.

Potter, W.D. 1961. Peak rates of runoff from small watersheds. Hydraulic Design Series 2, U.S. Bureau of Public Roads, Washington, D.C.

Romkens, M.J.N. 1979. Interpretation of rainfall simulator data. In Proceedings of a Rainfall Simulator Workshop, pp. 96-100. Tucson, Arizona: U.S. Department of Agriculture, ARM-W-10.

Rothacher, J., C.T. Dryness, and R.L. Fredricksen. 1967. Hydrologic and related characteristics of three small watersheds in the Oregon Cascades. Pacific Northwest Forest and Range Experiment Station, U.S. Forest Service, Portland, Oregon.

Schumm, S.A. 1956. The evolution of drainage systems and slopes in badlands at Perth Amboy, New Jersey. Geological Society of America Bulletin 67: 597-646.

Skinner, Q.D. et al. 1985. The effects of selected grazing treatments on channel morphology and sediment within the riparian zone of Fifteen Mile Creek. Annual Report to E.J. Fanning, Wyoming Department of Environmental Quality, Cheyenne, Wyoming.

Skinner, Q.D. et al. 1982. The effects of selected grazing treatments on channel morphology and sediment within the riparian zone of Fifteen Mile Creek. Report to E.J. Fanning, Wyoming Department of Environmental Quality, Cheyenne, Wyoming.

Smith, K.G. 1950. Standards for grading texture of erosional topography. American Journal of Science 248:655-668.

Strahler, A.N. 1957. Quantitative analysis of watershed geomorphology. American Geophycial Union Transactions 38:913-920.

Strahler, A.N. 1964. Quantitative geomorphology of drainage basins and channel networks. In Handbook of Applied Hydrology, ed. V.T. Chow, section 4-II. New York: McGraw-Hill.

Svatos, V.C. 1979. A case study of the analysis of the capability of undeveloped lands to contribute to water quality degradation. In Computer Mapping in Natural Resources and the Environment. Cambridge: Harvard University Press.

Taylor, A.B. and H.E. Schwartz. 1952. Unit-hydrograph lag and peak flow related to basin characteristics. American Geophysical Union Transactions 33:235-246.

Vold, T., M.W. Sondheim, N.K. Nagpal. 1985. Computer assisted mapping of soil erosion potential. Canadian Journal of Soil Science 65:411-418.

Warrington, G.E. 1980. Surface erosion. In An Approach to Water Resources Evaluation of Non-Point Silvicultural Sources (A Procedural Handbook), ed. L.A. Mulkey, Chapter IV. Athens, Georgia: U.S. Environmental Protection Agency.

Wilson, B. 1983. Fifteen Mile suspended sediment monitoring. Unpublished technical report, U.S. Bureau of Land Management, Worland, Wyoming.

Wischmeier, W.H. 1959. A rainfall erosion index for a universal soil-loss equation. Soil Science Society of America, Proceedings 23:246-249.

Wischmeier, W.H. and D.W. Smith. 1958. Rainfall energy and its relationship to soil loss. American Geophysical Union, Transactions 39:285-291.

Wischmeier, W.H. and D.W. Smith. 1965. Predicting rainfall-erosion losses from cropland east of the Rocky Mountains. U.S. Department of Agriculture Handbook 282, Washington, D.C.

Wood, M.K. and W.H. Blackburn. 1981. Grazing systems: their influence on infiltration rates in the Rolling Plains of Texas. Journal of Range Management 34:331-335.

Wood, M.K., G.B. Donart, and M. Weltz. 1986. Comparative infiltration rates and sediment production on fertilized and grazed blue grama rangeland. Journal of Range Management 39:371-374.

Yochem, T. and G. Rosenlieb. 1978. Evaluation of the discharge and suspended sediment load of Fifteen Mile Creek, 1952-1972. Unpublished technical report to the U.S. Bureau of Land Management, Worland, Wyoming.

Young, R.A. and R.E. Burwell. 1972. Prediction of runoff and erosion from natural rainfall runoff using a rainfall simulator. Soil Science Society of America, Proceedings 36:827-830.

Zachar, D. 1982. Soil Erosion. New York: Elsevier.

APPENDIX A

FORTRAN PROGRAM FOR CALCULATING EROSION AND RUNOFF FROM THE STUDY PLOTS

```
      PROGRAM MUDD (INPUT, OUTPUT)
C COMPUTE TOTAL SEDIMENT AND RUNOFF FOR SIMULATION EXPERIMENTS
C LARRY DOLAN DEC. 1987
C PROGRAM VARIABLES
C* CONC - SEDIMENT CONCENTRATION IN SAMPLE (MG/L)
C* NET  - TOTAL VOLUME OF WATER IN SAMPLE (ML)
C* FILLT - TIME IT TOOK BOTTLE TO FILL
C* TIMEP - TIME PERIOD SAMPLE REPRESENTED
C* SPLASH - WEIGHT OF SEDIMENT COLLECTED IN FUNNEL TROUGH (GRAMS)
C* RUNOFF - RUNOFF FOR EACH SAMPLING PERIOD
C* SED - TOTAL SEDIMENT FOR EACH SAMPLING PRERIOD
C* TOTALW - TOTAL RUNOFF FROM PLOT FOR EXPERIMENT
C* TOTALS - TOTAL SEDIMENT CARRIED IN RUNOFF
C* SEDT - TOTAL SOIL LOSS FROM PLOT FOR EXPERIMENT
C* NUM - EXPERIMENT NUMBER
      REAL CONC(4), NET(4), FILLT(4), TIMEP(4), SPLASH
      REAL RUNOFF, SED, TOTALW, TOTALS, SEDT, NUM
      INTEGER N
  5   TOTALW = 0
      TOTALS = 0
C READ NUMBER OF SAMPLES  AND SAMPLE NUMBER
      READ (*, *, END = 900) NUM, N
C READ IN SEDIMENT AND TIME VALUES AND PRINT
      DO 10 I = 1,N
        READ *,  CONC(I), NET(I), FILLT(I), TIMEP(I)
        PRINT *, CONC(I),NET(I), FILLT(I), TIMEP(I)
   10 CONTINUE
C READ IN SPLASH SEDIMENT
      READ *, SPLASH
C CALCULATE THE TOTAL RUNOFF AND TOTAL SEDIMENT FOR EXPERIMENT
      DO 20 I = 1,N
        RUNOFF = NET(I) *TIMEP(I) / FILLT(I)
        SED = (NET(I) *TIMEP(I) /FILLT(I)) /1000 *(CONC(I)/ 1000)
        TOTALW = TOTALW + RUNOFF
        TOTALS = TOTALS + SED
 20   CONTINUE
C ADD SPLASH SEDIMENT TO THAT CARRIED IN RUNOFF
      SEDT = TOTALS + SPLASH
C PRINT SAMPLE NUMBER AND TOTALS FOR SEDIMENT AND RUNOFF
      PRINT *, 'SAMPLE NUMBER', NUM
      PRINT *, 'TOTAL RUNOFF =', TOTALW, 'TOTAL SEDIMENT =', SEDT
C DO NEXT EXPERIMENT
      GO TO 5
 900  END
```

APPENDIX B

SOIL ANALYSIS DATA AND CATEGORIZATION OF SOIL TEXTURE

Soil Analysis Data

Site	% Sand (.05-2 mm)	% Coarse Silt (.05-.005 mm)	% Fine Silt (.005-.002 mm)	% Clay (<.002 mm)	Texture	Texture Index
1	32.8	16.3	30.6	20.3	Loam	2.38
2	40	32.3	8.0	19.7	Loam	2.07
3	49.6	20.2	8.1	22.1	Loam	2.03
4	37.4	24.2	12.2	26.2	Loam	2.27
5	53.5	16.2	6.0	24.3	Sandy clay loam	2.01
6	22.7	20.4	20.4	36.5	Clay loam	2.71
7	55.5	14.2	6.1	24.2	Sandy clay loam	1.99
8	75.9	6.0	2.0	16.1	Sandy loam	1.58
9	11.7	12.3	24.7	51.3	Clay	3.16
10A	18.9	40.6	12.2	28.3	Silty clay loam	2.50
10B	47.5	20.2	8.1	24.2	Loam	2.09
11	14.1	34.8	16.4	34.7	Silty clay loam	2.72
12	35.5	34.3	8.0	22.2	Loam	2.17
13	54.0	18.2	8.1	19.7	Loam	1.94
14	63.7	12.1	6.1	18.1	Sandy loam	1.79
15A	7.4	8.2	18.5	65.9	Clay	3.43
15B	32.9	14.3	12.2	40.6	Clay loam	2.61
16	57.7	14.1	6.0	22.2	Sandy clay loam	1.92
17	45.5	8.1	14.1	32.3	Sandy clay loam	2.33
18	69.9	10.0	4.0	16.1	Sandy loam	1.66

Soil Analysis Data (cont.)

Site	% Sand (.05-2 mm)	% Coarse Silt (.05-.005 mm)	% Fine Silt (.005-.002 mm)	% Clay (<.002 mm)	Texture	Texture Index
19	49.5	20.2	6	24.3	Sandy clay loam	2.05
20	65.8	6.0	6.0	22.2	Sandy clay loam	1.85
21	61.8	8.0	8.0	22.2	Sandy clay loam	1.90
22	51.3	16.2	6.1	26.4	Sandy clay loam	2.08
23	47.3	10.1	10.2	32.4	Sandy clay loam	2.27
24	71.9	8.0	4.0	16.1	Sandy loam	1.52
25	26.9	24.4	16.2	32.5	Clay loam	2.54
26	29.3	38.4	12.1	20.2	Silt loam	2.23
27	11.1	12.4	16.6	59.9	Clay	3.24
28	65.7	12.1	4.0	18.2	Sandy loam	1.75
29	0	6.2	25.0	68.8	Clay	3.63
30	2.3	18.7	18.7	60.3	Clay	3.37
31	34.9	14.2	16.3	34.6	Clay loam	2.51
32	24.7	26.4	20.4	28.5	Clay loam	2.53
33	15.8	10.3	12.3	61.6	Clay	3.20
34	73.9	6.0	2.0	18.1	Sandy loam	1.64
35	0	10.3	22.7	67	Clay	3.57
36	59.9	20.1	4.0	16.0	Sandy loam	1.77
37	37.5	26.2	14.1	22.2	loam	2.21

APPENDIX C

VEGETATION DENSITIES AND SOIL TEXTURE

VALUES ASSIGNED TO RANGE SITES

(Site write-up areas)

Vegetation Densities for Range Sites

From: Soil Inventory - Grass Creek, Wyoming, (Knox et al. 1979)

Range Site	Vegetation Density (percent ground cover)	Mean Vegetation Density* (used in mapping)
Sandy (SY)	40 - 50	45
Shallow Sandy (SWSY)	20 - 30	25
Laomy (LY)	30 - 40	35
Shallow Loamy (SWLY)	20 - 30	25
Saline Upland (SU)	10 - 20	15
Saline Lowland (SL)	40 - 50	45
Clayey (CY)	25 - 35	30
Rock Outcrop	0	0

*Note: When more than one range site type was identified in a site write-up area (SWA) an average vegetation density was calculated for the SWA using these values.

Soil Textures for Range Sites

Range Site	Soil Textures Associated with Site[a]	Range of Soil Texture Index Values[b]	Median Texture Value (used in mapping)
Sandy (SY) and Shallow Sandy (SWSY)	find sandy loams, sandy loams, loamy fine sands	1.5 - 2.0	1.75
Loamy (LY) and Shallow Loamy (SWLY)	sandy loams, loams, silt loams, sandy clay loams, silty clay loams, clay loams	1.9 - 2.7	2.3
Saline Upland (SU) and Saline Lowland (SL)	Variable	NA	Used data from surrounding soils and soil maps and descriptions[c]
Clayey (CY)	silty clays, clay loams, silty clay loams, clays	2.7 - 3.7	3.2
Rock outcrop (RO)	NA	NA	Used Texture Index of surrounding soils

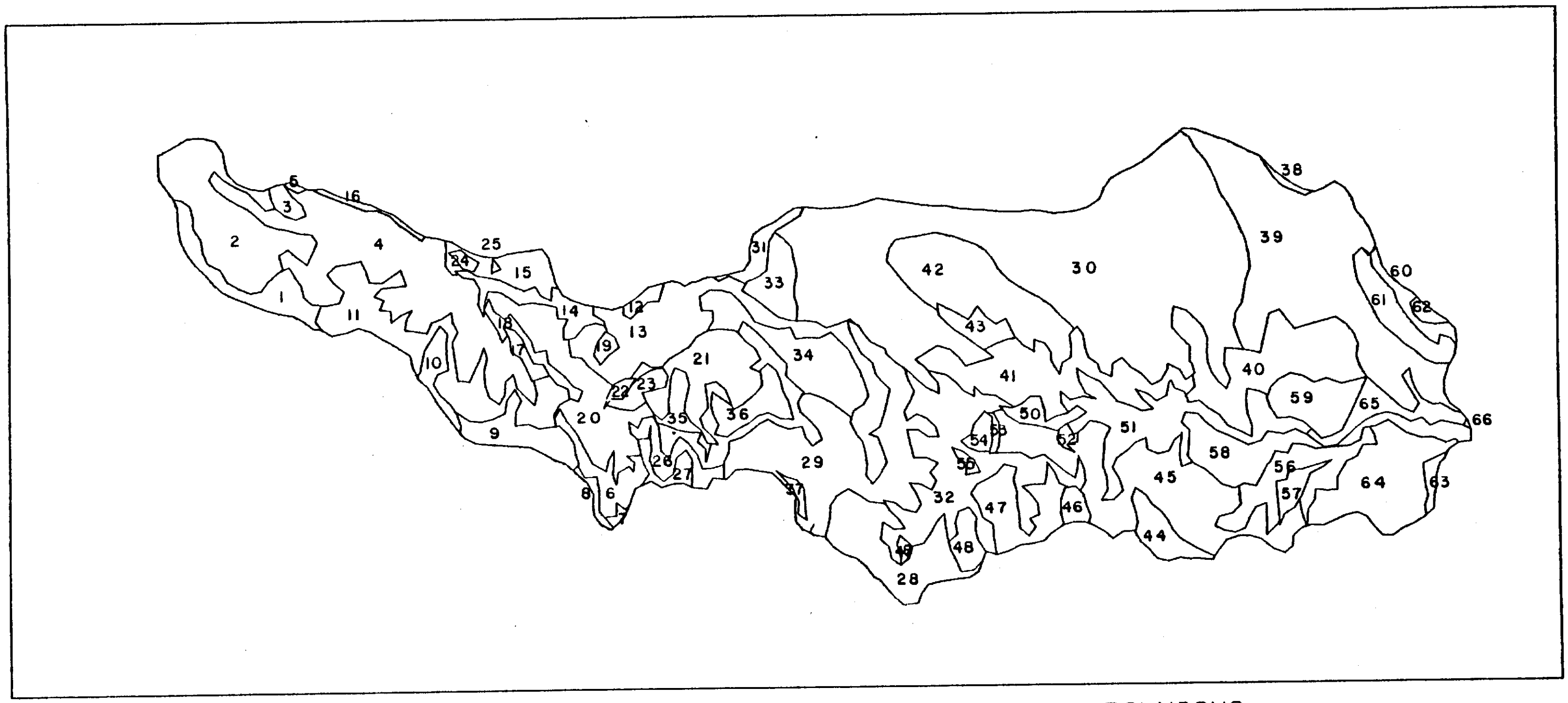
[a] From Soil Inventory: Grass Creek Area, Wyoming (Knox et al. 1979)

[b] From surface soil sample analysis data

[c] Soil survey of Washakie County, Wyoming (USDA 1983)

APPENDIX D

FINAL POLYGON MAP USED TO PREDICT EROSION AND RUNOFF PRODUCTION AND VALUES FOR SLOPE GRADIENT, VEGETATION DENSITY, SOIL TEXTURE, RUNOFF, AND SEDIMENT PRODUCTION FOR EACH OF THE 66 POLYGONS



MIDDLE FORK OF FIFTEENMILE CREEK SUBBASIN - POLYGONS

Polygon	Slope	Vegetation Density	Soil Texture	Runoff (centimeters)	Sediment (tons/hec.)
1.	1.0	35	2.30	2.42	3.08
2.	10.0	30	3.20	5.02	10.33
3.	3.5	30	3.20	4.52	6.21
4.	25.0	30	3.20	5.46	33.43
5.	3.5	30	3.20	4.52	6.21
6.	45.0	0	3.20	6.43	301.28
7.	25.0	30	3.20	5.46	33.43
8.	10.0	30	3.20	5.02	10.33
9.	3.5	30	3.20	4.52	6.21
10.	1.0	30	3.20	3.92	5.11
11.	10.0	30	3.20	5.02	10.33
12.	3.5	15	3.20	4.86	8.52
13.	10.0	30	3.20	5.02	10.33
14.	3.5	45	3.20	4.17	4.53
15.	25.0	0	3.20	6.15	62.95
16.	3.5	30	3.20	4.52	6.21
17.	3.5	30	3.20	4.52	6.21
18.	45.0	0	3.20	6.43	301.28
19.	3.5	15	3.20	4.86	8.52
20.	25.0	0	3.20	6.15	62.95
21.	3.5	15	3.20	4.86	8.52
22.	25.0	0	3.20	6.15	62.95
23.	10.0	15	3.20	5.36	14.18
24.	45.0	0	3.20	6.43	301.28
25.	45.0	0	3.20	6.43	301.28
26.	45.0	0	3.20	6.43	301.28
27.	25.0	0	3.20	6.15	62.95
28.	1.0	45	1.75	1.05	1.95
29.	3.5	15	3.20	4.86	8.52
30.	1.0	25	2.30	2.65	3.80
31.	3.5	25	2.30	3.25	4.63
32.	10.0	30	1.75	2.49	5.42
33.	1.0	15	2.30	2.88	4.70
34.	3.5	45	2.30	2.79	3.03
35.	25.0	0	3.20	6.15	62.95
36.	45.0	0	3.20	6.43	301.28
37.	25.0	15	3.20	5.80	45.87
38.	3.5	45	1.75	1.64	2.38
39.	1.0	45	1.75	1.05	1.95
40.	3.5	45	1.75	1.64	2.38
41.	3.5	15	3.20	4.86	8.52
42.	1.0	15	2.30	2.88	4.70
43.	3.5	25	2.30	3.25	4.63
44.	1.0	15	1.75	1.74	3.68
45.	3.5	15	3.20	4.86	8.52

Polygon	Slope	Vegetation Density	Soil Texture	Runoff (centimeters)	Sediment (tons/hec.)
46.	1.0	45	1.75	1.05	1.95
47.	3.5	15	3.20	4.86	8.52
48.	3.5	15	3.20	4.86	8.52
49.	3.5	45	1.75	1.64	2.38
50.	1.0	45	2.30	2.19	2.49
51.	10.0	15	3.20	5.36	14.18
52.	25.0	15	3.20	5.80	45.87
53.	25.0	15	3.20	5.80	45.87
54.	3.5	45	1.75	1.64	2.38
55.	3.5	30	1.75	1.99	3.26
56.	10.0	15	2.30	3.98	9.50
57.	1.0	15	2.30	2.98	4.70
58.	1.0	45	2.30	2.19	2.49
59.	1.0	45	1.75	1.05	1.95
60.	10.0	25	2.30	3.75	7.70
61.	3.5	25	2.30	3.25	4.63
62.	1.0	15	2.30	2.98	4.70
63.	10.0	15	2.30	3.98	9.50
64.	3.5	15	3.20	4.86	8.52
65.	1.0	45	2.30	2.19	2.49
66.	10.0	15	3.20	5.36	14.18

APPENDIX E

SITE DATA

(Used in Regression Analysis)

Site Data

Site	Vegetation Density (percent)	Vegetation Frequency (# of plants)	Litter Density (percent)	Slope Gradient (percent)	Slope Aspect (degrees)	Soil Texture Index	Total Runoff (liters)	Total Sediment (grams)
1A	50	260	10	3	100	2.38	7.85	36.7
B	60	148	20	3	100	2.38	1.02	50.0
2A	35	57	20	2.5	80	2.07	4.26	213
B	30	14	30	2.5	80	2.07	3.20	28.0
3A	50	120	10	1	100	2.03	6.15	65.2
B	65	120	10	1	100	2.03	2.52	75.0
4A	25	115	5	7	250	2.27	20.0	373
B	25	140	5	7	250	2.27	21.5	347
5A	40	95	15	11	70	2.01	5.46	141
B	40	50	10	11	70	2.01	5.58	321
6A	30	16	10	9	230	2.71	18.7	228
B	35	20	10	9	230	2.71	18.7	140
7A	50	31	25	3.5	220	1.99	1.81	52.9
B	40	27	25	3.5	220	1.99	1.95	52.8
8A	70	98	25	6	90	1.58	.543	52.0
B	65	72	25	6	90	1.58	.543	57.0

Site Data (cont.)

Site	Vegetation Density (percent)	Vegetation Frequency (# of plants)	Litter Density (percent)	Slope Gradient (percent)	Slope Aspect (degrees)	Soil Texture Index	Total Runoff (liters)	Total Sediment (grams)
9A	25	15	5	1.5	140	3.16	21.7	277
B	30	43	5	1.5	140	3.16	19.4	140
10A	60	13	15	3	190	2.50	10.04	78.8
B	40	10	10	3	190	2.09	8.30	116
11A	40	6	20	27	185	2.72	17.7	954
B	60	15	40	27	185	2.72	15.0	1410
12A	10	5	5	25	20	2.17	16.8	536
B	20	9	10	25	20	2.17	17.6	698
13A	75	12	40	2.5	200	1.94	3.22	73.1
B	70	10	40	2.5	200	1.94	5.40	91.7
14A	70	15	50	1.5	200	1.79	1.02	43.5
B	70	18	50	1.5	200	1.79	4.14	66.7
15A	20	2	5	21	50	3.43	16.3	942
B	40	10	10	21	50	2.61	22.3	963
16A	50	43	25	6	260	1.92	10.8	128
B	40	27	10	6	260	1.92	14.9	121

Site Data (cont.)

Site	Vegetation Density (percent)	Vegetation Frequency (# of plants)	Litter Density (percent)	Slope Gradient (percent)	Slope Aspect (degrees)	Soil Texture Index	Total Runoff (liters)	Total Sediment (grams)
17A	90	60	80	2.5	230	2.33	7.94	19.2
B	80	46	70	2.5	230	2.33	13.1	20.4
18A	80	120	70	1.5	330	1.66	4.58	41.5
B	90	97	80	1.5	330	1.66	.790	31.2
19A	60	78	70	4	340	2.05	1.75	72.2
B	40	90	50	4	340	2.05	3.09	91.1
20A	70	120	30	12.5	340	1.85	12.1	222
B	70	108	30	12.5	340	1.85	12.1	112
21A	25	37	10	22	170	1.90	10.8	929
B	25	37	10	22	170	1.90	7.16	1040
22A	25	35	10	6	30	2.08	14.6	225
B	25	21	10	6	30	2.08	16.0	452
23A	80	27	50	5	320	2.27	8.84	120
B	90	48	70	5	320	2.27	2.74	58.4
24A	40	34	40	4	240	1.52	2.33	111
B	75	58	40	4	240	1.52	.0634	67.0

Site Data (cont.)

Site	Vegetation Density (percent)	Vegetation Frequency (# of plants)	Litter Density (percent)	Slope Gradient (percent)	Slope Aspect (degrees)	Soil Texture Index	Total Runoff (liters)	Total Sediment (grams)
25A	15	2	5	5	270	2.54	21.9	1570
B	20	1	5	5	270	2.54	22.0	1230
26A	45	11	20	1.5	320	2.23	5.91	90.6
B	40	7	25	1.5	320	2.23	6.75	83.6
27A	35	2	5	20	120	3.24	18.6	1460
B	40	4	5	20	120	3.24	16.1	1210
28A	90	88	90	8	120	1.75	5.87	32.6
B	95	98	95	8	120	1.75	5.46	17.1
29A	50	105	50	1	190	3.63	11.9	112
B	60	116	50	1	190	3.63	7.63	88.2
30A	60	64	20	5	320	3.37	16.2	291
B	65	31	25	5	320	3.37	14.0	76.6
31A	100	98	100	34	140	2.51	3.08	1.61
B	100	112	100	34	140	2.51	3.15	2.98

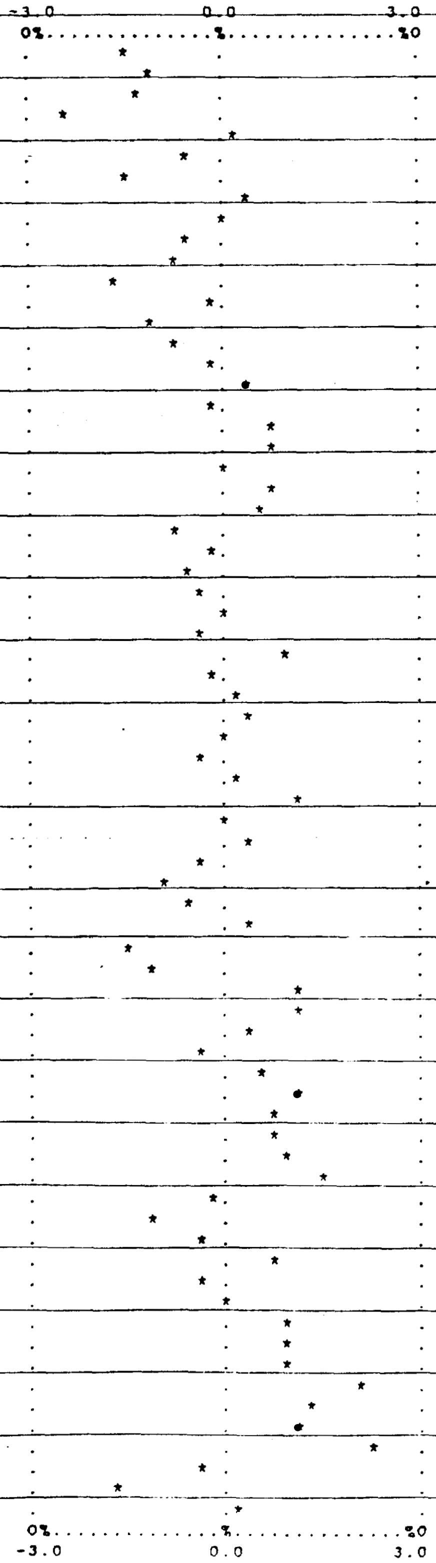
Site Data (cont.)

Site	Vegetation Density (percent)	Vegetation Frequency (# of plants)	Litter Density (percent)	Slope Gradient (percent)	Slope Aspect (degrees)	Soil Texture Index	Total Runoff (liters)	Total Sediment (grams)
32A	60	26	50	8	100	2.53	11.6	151
B	60	35	40	8	90	2.53	11.6	83.7
33A	0	0	0	26	170	3.20	17.2	1990
B	0	0	0	26	170	3.20	22.8	2860
34A	40	63	40	9	70	1.64	0	50.1
B	0	0	5	9	60	1.64	11.0	156
35A	0	0	0	40	210	3.57	24.4	2840
36A	75	132	75	8.5	10	1.77	4.73	45.5
B	65	102	65	8.5	10	1.77	6.50	98.6
37A	35	44	25	18	70	2.21	7.01	155
B	25	4	25	18	70	2.21	13.4	463

APPENDIX F

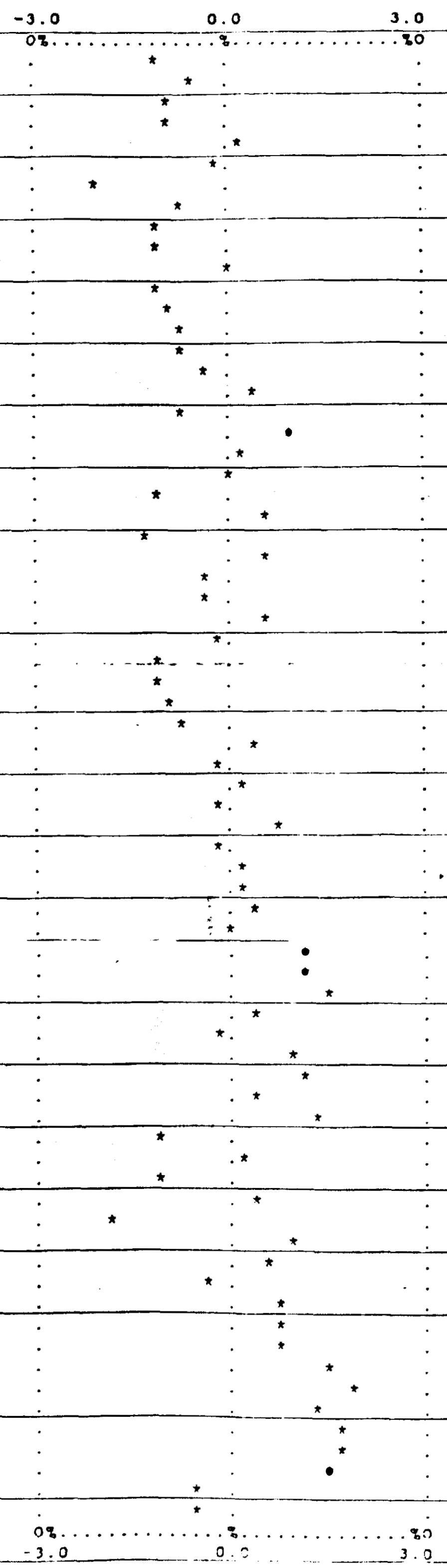
STANDARDIZED RESIDUAL PLOTS FOR EROSION AND RUNOFF PRODUCTION

PLOT OF STANDARDIZED RESIDUAL EROSION



SEQNUM	SED	*PRED	*RESID	*COOK D
1	1.2330	1.6259	-.3929	.0638
2	1.2833	1.5994	-.3161	.0294
3	1.3096	1.6909	-.3813	.0280
4	1.4472	2.0914	-.6442	.0901
5	1.4942	1.4316	.0625	.0011
6	1.5132	1.6717	-.1584	.0085
7	1.5647	1.9826	-.4179	.0167
8	1.6180	1.5232	.0949	.0018
9	1.6385	1.6338	.4659E-02	.0000
10	1.6580	1.8260	-.1680	.0054
11	1.6990	1.8910	-.1921	.0035
12	1.6998	2.1443	-.4445	.0338
13	1.7160	1.7486	-.0326	.0002
14	1.7226	2.0147	-.2920	.0118
15	1.7235	1.9231	-.1997	.0040
16	1.7574	1.7943	-.0369	.0002
17	1.7664	1.6652	.1012	.0030
18	1.8142	1.8573	-.0430	.0002
19	1.8241	1.6338	.1903	.0052
20	1.8261	1.6348	.1913	.0072
21	1.8585	1.8677	-.9145E-02	.0000
22	1.8639	1.6603	.2037	.0057
23	1.8751	1.7199	.1551	.0027
24	1.8842	2.1043	-.2201	.0221
25	1.8965	1.9292	-.0327	.0001
26	1.9227	2.0992	-.1765	.0030
27	1.9455	2.0715	-.1260	.0125
28	1.9571	1.9583	-.1126E-02	.0000
29	1.9595	2.0508	-.0913	.0010
30	1.9624	1.7060	.2563	.0077
31	1.9713	2.0040	-.0328	.0002
32	1.9939	1.9175	.0763	.0003
33	2.0453	1.9552	.0901	.0019
34	2.0492	2.0268	.0224	.0001
35	2.0492	2.1630	-.1138	.0096
36	2.0645	2.0168	.0477	.0003
37	2.0792	1.7568	.3224	.0187
38	2.0828	2.0997	-.0169	.0000
39	2.1072	2.0081	.0991	.0008
40	2.1461	2.2676	-.1214	.0062
41	2.1461	2.4003	-.2541	.0070
42	2.1492	2.2887	-.1395	.0016
43	2.1790	2.0992	.0798	.0006
44	2.1903	2.6106	-.4203	.0236
45	2.1931	2.5105	-.3174	.0701
46	2.3284	2.0456	.2828	.0140
47	2.3464	2.0268	.3195	.0213
48	2.3522	2.2561	.0961	.0018
49	2.3579	2.4460	-.0881	.0010
50	2.4425	2.3133	.1291	.0078
51	2.4639	2.1501	.3138	.0413
52	2.5065	2.2887	.2178	.0040
53	2.5403	2.3283	.2120	.0071
54	2.5717	2.3283	.2434	.0094
55	2.6551	2.2561	.3990	.0313
56	2.6656	2.7022	-.0366	.0002
57	2.7292	3.0583	-.3292	.0440
58	2.8439	2.9668	-.1229	.0054
59	2.9680	2.7808	.1872	.0108
60	2.9741	3.0792	-.1052	.0040
61	2.9795	2.9663	.0132	.0001
62	2.9836	2.7433	.2404	.0111
63	3.0170	2.7808	.2362	.0172
64	3.0828	2.8239	.2589	.0202
65	3.0899	2.5334	.5565	.0483
66	3.1492	2.7832	.3660	.0890
67	3.1644	2.8697	.2947	.0243
68	3.1959	2.5791	.6168	.0758
69	3.2989	3.3941	-.0952	.0041
70	3.4533	3.9272	-.4739	.2965
71	3.4564	3.3941	.0623	.0017
SEQNUM	SED	*PRED	*RESID	*COOK D

PLOT OF STANDARDIZED RESIDUAL RUNOFF (including all variables)



SEQNUM	VAR10	*PRED	*RESID	*COOK D
1	0	4.8380	-4.8380	.0190
2	.0630	2.6082	-2.5452	.0055
3	.5400	4.4114	-3.8714	.0138
4	.5430	4.4114	-3.8684	.0138
5	.7900	.1852	.6048	.0004
6	1.0200	2.1339	-1.1139	.0011
7	1.0200	9.5879	-8.5679	.0260
8	1.7500	5.1704	-3.4204	.0073
9	1.8100	6.7185	-4.9085	.0085
10	1.9500	6.7185	-4.7685	.0080
11	2.3300	2.6082	-.2782	.0001
12	2.5200	7.5180	-4.9980	.0460
13	2.7400	6.8361	-4.0961	.0131
14	3.0900	5.9766	-2.8866	.0036
15	3.2000	6.4157	-3.2157	.0042
16	3.2200	5.0305	-1.8105	.0015
17	4.1400	2.1339	2.0061	.0035
18	4.2600	7.3873	-3.1273	.0045
19	4.5800	.5051	4.0749	.0170
20	4.7300	4.0588	.6712	.0004
21	5.4000	5.0305	.3695	.0001
22	5.4600	10.5506	-5.0906	.0102
23	5.4600	3.3912	2.0688	.0049
24	5.5800	11.5221	-5.9421	.0167
25	5.8700	3.5208	2.3492	.0061
26	5.9100	7.8274	-1.9174	.0028
27	6.1500	7.5180	-1.3680	.0034
28	6.5000	4.4017	2.0983	.0039
29	6.7500	7.2927	-.5427	.0002
30	7.0100	11.4421	-4.4321	.0148
31	7.1600	11.9836	-4.8236	.0213
32	7.6300	11.6364	-4.0064	.0628
33	7.8500	11.2487	-3.3987	.0061
34	7.9400	5.9618	1.9782	.0038
35	8.3000	9.3525	-1.0525	.0007
36	8.8400	7.6423	1.1977	.0009
37	10.4000	11.4084	-1.0084	.0005
38	10.8000	7.6186	3.1814	.0032
39	10.8000	11.9836	-1.1836	.0013
40	11.0000	9.8204	1.1796	.0026
41	11.6000	10.6962	.9038	.0006
42	11.6000	10.1615	1.4385	.0020
43	11.9000	11.6364	.2636	.0003
44	12.1000	7.6738	4.4262	.0130
45	12.1000	7.6738	4.4262	.0130
46	13.1000	6.2818	6.8182	.0395
47	13.4000	11.4421	1.9579	.0029
48	14.0000	14.8042	-.8042	.0009
49	14.6000	10.5100	4.0900	.0073
50	14.9000	9.8141	5.0859	.0140
51	15.0000	13.7715	1.2285	.0034
52	16.0000	10.5100	5.4900	.0131
53	16.1000	20.5579	-4.4579	.0228
54	16.2000	15.3388	.8612	.0009
55	16.3000	21.4618	-5.1618	.0373
56	16.8000	15.2158	1.5842	.0027
57	17.2000	24.8522	-7.6522	.1423
58	17.6000	13.5550	4.0450	.0138
59	17.7000	15.4323	2.2677	.0071
60	18.6000	20.5579	-1.9579	.0044
61	18.7000	15.2586	3.4414	.0051
62	18.7000	15.2586	3.4414	.0051
63	19.4000	15.8018	3.5982	.0266
64	20.0000	13.7213	6.2787	.0276
65	21.5000	13.7213	7.7787	.0423
66	21.7000	15.8018	5.8982	.0715
67	21.9000	14.8938	7.0062	.0341
68	22.2000	14.8938	7.3062	.0370
69	22.3000	16.1614	6.1386	.0277
70	22.8000	24.8522	-2.0522	.0102
71	24.4000	26.7874	-2.3874	.0167

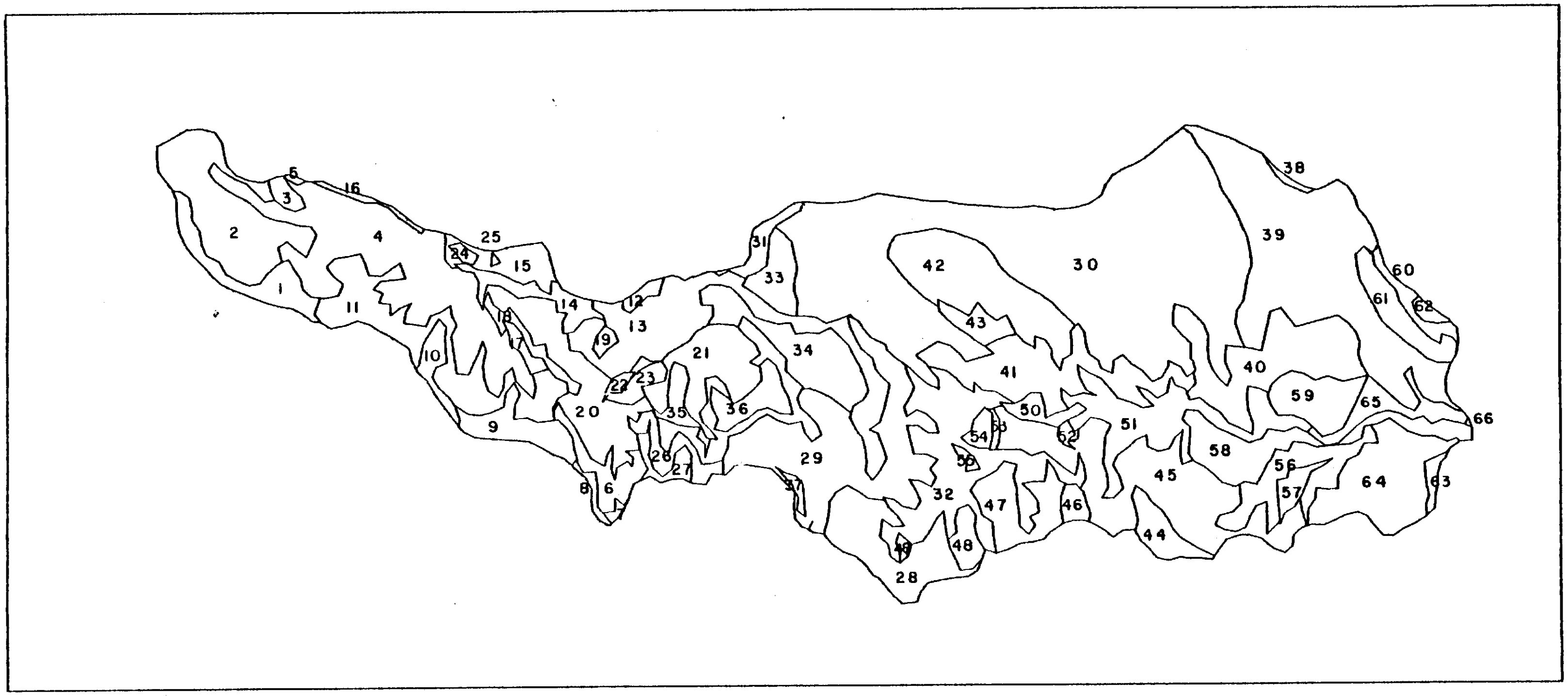
SEQNUM VAR10 *PRED *RESID *COOK D

~~PLOT OF STANDARDIZED RESIDUAL~~ RUNOFF (excluding litter)

SEQNUM	VAR10	*PRED	*RESID	*COOK D
~~1~~	~~0~~	~~6.8020~~	~~-6.8020~~	~~.0369~~
2	.0630	1.3818	-1.3188	.0015
3	.5400	2.9528	-2.4128	.0048
~~4~~	~~.5430~~	~~2.5268~~	~~-1.9838~~	~~.0034~~
5	.7900	-.6352	1.4252	.0024
6	1.0200	2.0083	-.9883	.0008
~~7~~	~~1.0200~~	~~8.7746~~	~~-7.7546~~	~~.0214~~
8	1.7500	7.1186	-5.3686	.0080
9	1.8100	6.9387	-5.1287	.0089
~~10~~	~~1.9500~~	~~7.7907~~	~~-5.8407~~	~~.0158~~
11	2.3300	4.3636	-2.0336	.0045
12	2.5200	4.2342	-1.7142	.0028
~~13~~	~~2.7400~~	~~6.4357~~	~~-3.6957~~	~~.0165~~
14	3.0900	8.8225	-5.7325	.0116
15	3.2000	8.8409	-5.6409	.0261
~~16~~	~~3.2200~~	~~4.2122~~	~~-.9922~~	~~.0005~~
17	4.1400	2.0083	2.1317	.0036
18	4.2600	8.4149	-4.1549	.0116
~~19~~	~~4.5800~~	~~.2167~~	~~4.3633~~	~~.0187~~
20	4.7300	4.6585	.0715	.0000
21	5.4000	4.6381	.7619	.0003
~~22~~	~~5.4600~~	~~10.6164~~	~~-5.1564~~	~~.0097~~
23	5.4600	2.8471	2.6129	.0115
24	5.5800	10.6164	-5.0364	.0092
~~25~~	~~5.8700~~	~~3.2731~~	~~2.5969~~	~~.0095~~
26	5.9100	8.1343	-2.2243	.0038
27	6.1500	5.5121	.6379	.0005
~~28~~	~~6.5000~~	~~5.5104~~	~~.9896~~	~~.0006~~
29	6.7500	8.5603	-1.8103	.0029
30	7.0100	13.3930	-6.3830	.0210
~~31~~	~~7.1600~~	~~12.3286~~	~~-5.1686~~	~~.0246~~
32	7.6300	13.7704	-6.1404	.1074
33	7.8500	9.6266	-1.7766	.0010
34	7.9400	5.8955	2.0445	.0049
35	8.3000	8.3123	-.0123	.0000
~~36~~	~~8.8400~~	~~7.2877~~	~~1.5523~~	~~.0018~~
37	10.4000	10.0670	.3330	.0001
38	10.8000	7.8946	2.9054	.0024
39	10.8000	12.3286	-1.5286	.0021
~~40~~	~~11.0000~~	~~10.2098~~	~~.7902~~	~~.0017~~
41	11.6000	11.8064	-.2064	.0000
42	11.6000	11.8064	-.2064	.0000
~~43~~	~~11.9000~~	~~14.6223~~	~~-2.7223~~	~~.0203~~
44	12.1000	6.6543	5.4457	.0263
~~45~~	~~12.1000~~	~~6.6543~~	~~5.4457~~	~~.0263~~
46	13.1000	6.7474	6.3526	.0315
47	13.4000	14.2449	-.8449	.0004
~~48~~	~~14.0000~~	~~14.8500~~	~~-.8500~~	~~.0011~~
49	14.6000	10.8194	3.7806	.0082
50	14.9000	8.7465	6.1535	.0134
~~51~~	~~15.0000~~	~~15.1564~~	~~-.1564~~	~~.0000~~
52	16.0000	10.8194	5.1806	.0153
53	16.1000	18.9614	-2.8614	.0099
~~54~~	~~16.2000~~	~~15.2760~~	~~.9240~~	~~.0011~~
55	16.3000	21.6914	-5.3914	.0373
56	16.8000	15.3844	1.4156	.0023
~~57~~	~~17.2000~~	~~22.8344~~	~~-5.6344~~	~~.0486~~
58	17.6000	14.5325	3.0675	.0085
59	17.7000	16.8603	.8397	.0007
~~60~~	~~18.6000~~	~~19.3873~~	~~-.7873~~	~~.0007~~
61	18.7000	15.3379	3.3621	.0045
62	18.7000	15.7639	2.9361	.0036
~~63~~	~~19.4000~~	~~14.7276~~	~~4.6724~~	~~.0359~~
64	20.0000	12.5700	7.4300	.0241
65	21.5000	12.5700	8.9300	.0347
~~66~~	~~21.7000~~	~~15.1536~~	~~6.5464~~	~~.0774~~
67	21.9000	14.8066	7.0934	.0391
68	22.2000	14.3806	7.8194	.0378
~~69~~	~~22.3000~~	~~15.8296~~	~~6.4704~~	~~.0300~~
70	22.8000	22.8344	-.0344	.0000
71	24.4000	24.9873	-.5873	.0007
SEQNUM	VAR10	*PRED	*RESID	*COOK D

APPENDIX G

POLYGON MAP AND DATA USED FOR AREA - GROSS EROSION CALCULATIONS



MIDDLE FORK OF FIFTEENMILE CREEK SUBBASIN - POLYGONS

POLYGON	% TOTAL AREA	TONS/HECTARE	TONS
1	1.1300	3.08	375.92
2	3.1400	10.33	3503.47
3	.2210	6.21	148.24
4	5.7300	33.43	20689.97
5	.0320	6.21	21.46
6	.7870	301.28	25610.25
7	.0670	33.43	241.92
8	.1410	10.33	157.32
9	1.0000	6.21	670.75
10	.4430	5.11	244.51
11	2.9600	10.33	3302.64
12	.1750	8.52	161.04
13	3.7400	10.33	4172.93
14	.7260	4.53	355.23
15	.9580	62.95	6513.73
16	.1640	6.21	110.00
17	.2160	6.21	144.88
18	.3900	301.28	12691.23
19	.1330	8.52	122.39
20	3.7900	62.95	25769.37
21	1.8000	8.52	1656.46
22	.1120	62.95	761.52
23	.3250	14.18	497.77
24	.0960	301.28	3123.99
25	.0190	301.28	618.29
26	.6210	301.28	20208.34
27	.3250	62.95	2209.77
28	2.2000	1.95	463.37
29	4.8700	8.52	4481.64
30	17.4000	3.80	7141.70
31	.4240	4.63	212.04
32	3.9400	5.42	2306.56
33	.7830	4.70	397.49
34	1.9400	3.03	634.91
35	.4160	62.95	2828.51
36	.7610	301.28	24754.17
37	.1070	45.37	530.13
38	.0880	2.38	22.52
39	7.3900	1.95	1556.50
40	3.1000	2.38	796.91
41	2.3800	8.52	2650.34
42	3.0900	4.70	1568.65
43	.4970	4.63	248.55
44	.6890	3.68	273.36
45	4.5300	8.52	4168.76

Polygon	% Total Area	Tons/Hect.	Tons
46	.2590	1.95	54.55
47	1.3500	8.52	1242.34
48	.4320	8.52	397.55
49	.0770	2.38	19.79
50	.3840	2.49	103.28
51	2.6000	14.18	3982.16
52	.0980	45.87	485.54
53	.0840	45.87	416.18
54	.2330	2.38	59.90
55	.0810	3.26	28.52
56	1.4700	9.50	1508.38
57	.3350	4.70	170.06
58	1.8900	2.49	508.31
59	1.2100	1.95	254.85
60	.4100	7.70	340.99
61	.9550	4.63	477.59
62	.1430	4.70	72.59
63	.1830	9.50	187.78
64	2.6100	8.52	2401.87
65	.8680	2.49	233.45
66	.0100	14.18	15.32

TOTAL TONS =202091.0949019

Total Area = 10800 Hectares (41.8 km^2)