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Rill-Interrill Erosion and Deposition Model of Stripmine Hydrology

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RILL-INTERRILL EROSION AND DEPOSITION MODEL OF STRIPMINE HYDROLOGY

by

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FOREWORD

The Federal Water Pollution Control Act Amendments of 1972, in part, stress the control of nonpoint source pollution. Sections 102 (C-1), 208 (b-2,F) and 304(e) authorize basin scale development of water quality control plans and provide for area-wide waste treatment management. The act and the amendments include, when warranted, waters from agriculturally and silviculturally related nonpoint sources, and requires the issuance of guidelines for both identifying and evaluating the nature and extent of nonpoint source pollutants and the methods to control these sources. Research at the Northeast Watershed Research Center contributes to the aforementioned goals. The major objectives of the Center are to:

- Study the major hydrologic and water-quality associated problems of the Northeastern U.S. and
- Develop hydrologic and water quality simulation capability useful for land-use planning. Initial emphasis is on the hydrologically most severe land uses of the Northeast.

Within the context of the Center's objectives, stripmining for coal ranks as a major and hydrologically severe land use. In addition, once the site is reclaimed and the conditions of the mining permit are met, stripmined areas revert legally from point to nonpoint sources. As a result, the hydrologic, physical, and chemical behavior of the reclaimed land needs to be understood directly and in terms of control practices before the goals of Sections 102, 208 and 304 can be fully met.

Signed:

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ABSTRACT

An erosion-sediment yield model (labeled KEM) was developed from the continuity consideration for sediment transport and from equations describing rill and interrill erosion. This computerized model is based on dividing the upland areas into a grid containing rill and interrill zones and on the Universal Soil Loss Equation (USLE). The USLE is used to estimate the sediment contribution from the interrill areas. Prediction of soil loss from the interrill areas is based on the premise that both raindrop impact and overland flow energy can create soil erosion. The rill flow carries the interrill erosion along with the rill scour. Rill transport capacity governs the amount of removed soil from the site. If the flow transport capacity is less than the available eroded soil, net erosion equals the transport capacity and the excess sediment is deposited in the flow paths. Otherwise, all eroded soil will move downslope and out of the watershed.

The model was tested by simulating actual events on a small watershed in Central Pennsylvania for summer storms during 1981. Applying the model to this stripmined and reclaimed area created a set of information about the location and amount of watershed erosion and deposition. The areal distribution of erosion and deposition was compared with measured data. The model performed satisfactorily in predicting soil loss from the site.

CONCLUSIONS

An erosion sediment yield model (KEM) based upon partial area hydrology has been developed and tested. The model was based on the fundamental mechanics of erosion, rill transport, and deposition. This computer model was formulated from the continuity consideration for sediment transport and from equations describing rill and interrill erosion. The model considers the watershed to be divided into subwatersheds so that the error in selecting the parameters for the Universal Soil Loss Equation can be reduced.

Prediction of soil loss was based on the premise that both raindrop impact and overland flow energy can create soil erosion anywhere on the watershed. Depending upon sediment transport capacity of the flow, sediment may or may not move downslope.

The erosion process has been separated into rill and interrill components. It was assumed that interrill erosion resulted from the rainfall impact and the detached sediment was transported into microchannels (rills) by sheet flow occurring in the interrill areas. Erosion in the rill was then considered to be a result of soil detachment in the rill and the transport capacity of the rill flow.

The model is able to generate rill sources and rill patterns as well as contributing interrill areas. Contributing interrill areas are portions of interrill areas that contribute sediment to rill microchannels. The model determines the eroded soil available for transport at all points of a watershed and net amounts of soil eroded for any area. The model can also predict sediment loads and timing of stream inputs. The model predicts areal distribution of erosion and deposition. This type of information could be used to plot iso-erosion and deposition maps.

To test the model, it was applied to a stripmined and reclaimed area in Central Pennsylvania. The model was executed for five storm events which occurred in Summer 1981 (June 1 to September 1). The rills and contributing interrill areas were generated for each storm event. Then, the location and amount of watershed erosion and deposition were determined. The outputs of all the storms were added to each other. The end result was a map showing erosion or deposition in each subwatershed.

The model outputs were compared with soil loss measured using erosion pins. The predicted results of erosion and deposition in terms of being one or the other, were in good agreement with measured data, the only discrepancy was in order of magnitude. Although the simulated results overpredicted by 25% the measured values, it is believed that the model is accurate enough to be useful on mined and reclaimed areas.

Although this model requires many types of parameters, most of them can be determined from published information or measured directly from the maps or in the field. This model could increase the accuracy of sediment yield predictions by allowing determination of zone and subwatersheds contributions to the total sediment yield. The model could be useful in evaluating the environmental impact of land use practices. It also may serve as basis for reservoir and channel design and land use planning.

Many problems have occurred while attempting to develop and apply this model. It is believed that the following suggestions will be of value for future studies involving erosion modeling from upland areas:

(1) Further studies are needed to enhance this model for unsteady conditions.

(2) Many sediment transport equations are available to calculate the sediment transport capacity. However, most of those equations were derived for application in rivers where water is deep. There is a need to evaluate the applicability of these equations in a shallow flow condition.

(3) Model formulation did not include the ground water or subsurface flow. In humid regions where subsurface or ground water is dominant, there is a need to incorporate this effect into the model.

(4) Further studies are needed to determine how land use activities such as road building, construction, and logging will change parameters used in Philip's Equation and other parameters related to sediment yield.

(5) Further studies are helpful to identify the difference between the size distribution of the soil at source area and the sediment transported in the watershed.

(6) This model similates the water and sediment yield for individual storm. Further studies are suggested to incorporate the water and soil loss processes continuous simulation.

(7) Further studies are needed to evaluate the influence of rainfall energy on the transport capacity over land surfaces and on turbulent mixing in the rill water.

(8) Further studies are needed to extend the application of this model to a region where ground is frozen or covered with ice.

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SECTION 1

INTRODUCTION

1.1. Need for Study

Recently a sincere and dedicated concern has been shown by the public for preserving our natural resources. Two of the most important resources are soil and water. Continued sediment erosion and pollution of our waterways have led to serious problems currently being studied by engineers and the scientific community.

Among the existing problems facing the world, is the increase in population. The area of land is fixed, but population continues to grow. This increased population demands more homes, highways, and industries which in turn reduce the amount of land available for food production. Consequently, soil erosion and sedimentation are of particular importance in the evaluation of water and soil resources. Soil erosion could result in significant deterioration of the land's long term productive capability.

The erosion process and the resulting sediment are the most important problems, because they not only affect the water quality in the stream but also may restrict future land use. Also, most pesticides and nutrients attach themselves to the clay particles, and thus are carried away when erosion occurs. These eroded soils may enter the streams and pollute the natural water resources.

Soil erosion is the primary source of sedimentation, because eroded soil particles are transported to rivers and deposited. These sediments may result in the premature filling of lakes and reservoirs and reduce the capacity of rivers to carry flood flows. In irrigation systems, sediment may greatly reduce the carrying capacity of constructed artificial channels.

How can this situation be resolved to satisfy the needs and desires of an ever more demanding society with a limited supply of land resources? The problems associated with land use can be solved using the knowledge of land characteristics from which various land use opportunities can be interpreted. Mathematical modeling and system analysis techniques offer a unique opportunity to analyze various control technologies and provide methods to select those which are most efficient.

In upland areas, especially mountainous watersheds where soil erosion is likely to be a more serious problem, erosion models are needed to develop procedures for reservoir design and to assess the impact of changes including irrigation, urbanization, mining, and rural constructions. These models are highly beneficial as a design tool in developing plans to control soil loss and erosion damage on upland areas. Present models vary considerably with respect to generality and applicability. Most of them depend on a set of historical data to calibrate the unknown parameters. Thus, these models must be used with caution if significant changes in the basin land use have occurred or the events differ greatly from those in the calibration data.

Many methods are available to estimate soil erosion and sediment yield and one may ask, why should another model be developed? The answer to this has three parts:

(1) Although several equations have been developed to predict soil erosion, it has been pointed out by many investigators that the applicability of these soil loss equations may be exceeded when they are applied to a watershed because they were developed from research data on small plots for a particular land use and there is no assurance that a technique good on a small scale in one land resource area will apply to another.

(2) There is a new emphasis on evaluating the impact of changes in water quality and quantity with changes in land use. Thus, there is a need to develop an erosion model from basic principles to any conditions. Erosion is a complex phenomenon and should not be restricted to estimating only the amount of eroded soil from a watershed.

(3) Most models developed to predict soil erosion from a watershed usually consider the entire drainage area as contributing to erosion. Therefore, they reflect gradient and soil type along the entire slope length. This implies that the entire

watershed produces runoff. This type of approach cannot be correct because realistically only portions of a watershed can produce runoff.

1.2. Erosion and Its Problem

Erosion is the removal of soil particles from the land surface. This process is the result of energy developed by the water as it falls toward the earth and as it flows over the surface of the land.

Problems associated with soil erosion are many. Erosion on cropland degrades the productivity of the soil resource necessary for crop and food production. As a result of soil erosion, plant nutrients and fine particles are selectively removed causing poor soil tilth and increasing runoff because of poor infiltration.

Eroded soil not only reduces soil productivity, but also is a pollutant itself. It may carry soil-adsorbed chemicals, which are themselves pollutants. Sediment pollutes by muddying the water, clogging fish gills, covering nests and spawning grounds, and increasing the dissolved oxygen demand. In those communities in which surface water is a source of water supply, sediment removal from water for public use can be costly, because, large investments in the construction and operation of treatment facilities are generally required. Similarly, sediment deposition in stream channels, rivers, and lakes usually require costly removal.

1.3. Objectives

The major objective of this study is to develop a mathematical model having the following characteristics:

(1) Predict soil erosion from upland areas using the partial area concept.

(2) Predict probable location of rills and the total amount of sediment transported to a stream or sediment pond following a specific design storm.

(3) Use readily available data that will be user oriented.

The model is to be based on basic principles of erosion mechanics and experimental information available so that it can be used for simulating soil loss and sediment yield due to changes in land use.

1.4. Approach

In order to accomplish the objectives of this study, a model that describes the spatial changes in land use, geometry, and soil characteristics is needed. The idea that both raindrop impact and overland flow can create soil erosion and the partial area concept form the basis for this model.

Rill development is simulated on a computer. After generating the rill patterns, the contributing interrill areas are delineated.

The eroded soil from rills and contributing interrill areas is calculated and routed along the rill patterns. When the rill transport capacity exceeds the available detached soil, deposition does not occur. If the transport capacity is less than the total soil available to be transported, the amount of deposition is assumed to be the difference between the detached load and the rill transport capacity.

SECTION 2

LITERATURE REVIEW

Erosion prediction from upland areas is highly beneficial as a design tool in developing plans to control sediment loss and erosion damage. The relationship between rainfall, runoff (overland), soil erosion, and sediment yield has been studied by many specialists for many years. This review of literature assembles information concerning runoff (overland flow), soil erosion, and sediment yields. For clarity, this chapter is divided into three sections: soil erosion, overland flow, and soil loss determination.

2.1. Soil Erosion

Erosion is defined as the abrading of the land. It is the removal of soil materials by erosive agents and refers to two phases of the process of detaching and transporting. Erosion could be caused by wind or water, each has a different process and characteristics. Since wind erosion is not part of this study, it will not be discussed here.

Brant *et al.* (1972) have listed the most important sources of erosion and sediment yield:

(1) Natural erosion occurs from the weathering of soils, rocks, and uncultivated land, and geological abrasion.

(2) Agricultural erosion is a major sediment source due to the large area involved and the land distrubing effects of cultivation.

(3) Urban and rural erosion originates mainly from exposed bare soil in areas under construction or from lands disturbed by mining.

(4) Highway erosion is associated with the stripping of large areas of their vegetative protection during road construction (i.e., landslides).

(5) Stream bank, channel, and shoreline erosion from concentrated water flows and wave action in channels and floodplains.

Raindrops hitting the earth's surface initiate the process of soil erosion by water. Rainfall detaches soil particles by drop impact and transports them by splash. Detachment capacity of rainfall depends on the diameter of the raindrop, distribution, velocity, and total mass or kinetic energy at impact.

Raindrop impact and flowing water are the erosive agents involved in the erosion process. However, the forces of gravity and cohesion are working against the erosive agents. Therefore, erosion will take place whenever eroding forces exceed the forces of resistance. When there is no more surface storage capacity and the rainfall intensity exceeds the infiltration rate of the soil, there would be overland flow which moves the eroded soil particles downslope.

The basic factors affecting soil erosion from watersheds are climate, topography, soil, vegetative cover, and human activities. These factors are briefly described here.

2.1.1. Climate Condition

Rainfall is obviously the most important factor among the other major climatic factors of wind, temperature, and snow. Rainfall erosivity depends on the rainfall intensity, duration, frequency, and shear force exerted on the ground surface. Wischmeier and Smith (1958) found that the rainstorm parameter most highly correlated with soil loss from fallow ground was a product term: kinetic energy of the storm times maximum 30-minute rainfall intensity. This product is called the "rainfall erosion index" and explains 72 to 97 percent of the variation in individual storm erosion from tilled continuous fallow ground on each of six widely scattered soils (Smith and Wischmeier, 1962).

Raindrop splash and overland flow are major agents in transporting the eroded material. Overland flow is surface runoff which travels over the ground surface to a channel. Overland flow tends to be channelized and make rills and gullies, whereas splash erosion tends to remove soil particles from the surface as a uniform sheet layer.

Meyer _et al_. (1975a) studied effect of flow rate and canopy on rill erosion and found that soil loss due to the rill flow rate can be fitted by the equation:

$$E_T = E_I + D_R(Q - Q_C) \qquad (2.1)$$

where;

E_T = total rill and interrill erosion per unit of rill length (wt/time/length),

E_I = erosion rate on interrill areas per unit of rill length (wt/time/length),

D_R = detachment rate in rills per unit of rill length per unit of excess discharge (wt/time/length/discharge),

Q = rill discharge rate (discharge = vol/time),

Q_C = critical discharge below which rill erosion is negligible (vol/time), and

$E_T = E_I$ when $Q \leq Q_C$.

2.1.2. Topography

The effect of topography can be explained in terms of slope steepness and slope length.

2.1.2.a. Slope Steepness

Slope steepness is the main topographic feature that is highly correlated with soil erosion. Zingg (1940) studied the effect of degree of slope on soil loss and found that on slopes of less than 10 percent, erosion approximately doubled as slope, expressed as percentage, increased two-fold.

Foster and Martin (1969) found that on slopes above 20 percent, the erosion rate tended to level off for some conditions. Thus, they found that depending on bulk density, erosion on short slopes from 35 to 100% reached a maximum and then decreased as the slope steepened.

The influence of slope steepness on the transport capacity of the flow is also very important. Most studies show that transport capacity changes as some power greater than two of the energy grade line which approximately is equal to the land slope. Thus, the increase in land slope would increase transport capacity rapidly.

2.1.2.b. Slope Length

Zingg (1940) also explained the influence of slope length on the average erosion per unit area for a given slope. His expression was in the form of:

$$A = L^n \qquad (2.2)$$

where;

A = Average erosion per unit area,

L = slope length,

n = a coefficient.

Wischmeier and Smith (1965) used a value of n near n = 0.5 for most circumstances. However, Foster and Meyer (1972a) indicated that the value of n depends on the relative susceptibility of different soils to rilling and the resulting ratio of rill erosion to interrill erosion. They indicated that where soil loss is primarily from rills, n will approach one, but if the interrill erosion is dominant it will approach zero. Young and Mutchler (1969) also showed that n increases with increasing slope length because rill erosion increases faster than interrill erosion.

Smith *et al*. (1945) used five plots with lengths up to 270 ft. Erosion loss was measured at downslope intervals of 10 ft for five years and the best fitted equation was reported as:

$$Y = 0.016\ L^{0.57} \tag{2.3}$$

where;

Y = average depth of soil loss (ft),

L = slope length (ft).

2.1.3. Soil

The major factors affecting soil erosion are texture, structure, permeability, compactness, and infiltration capacity of the soil profile. Soil texture determines the permeability and erodibility of soil. Erodibility, detachability, and transportability of soil directly influence the rate and amount of soil erosion. However, under the same hydraulic, climatic, and vegetative cover different types of soil might have different erodibility and soil losses.

Middleton's (1930) effort to determine the erodibility of soils led to the suggestion that the "dispersion ratio" and "erosion ratio" as erosion indices relate erosion to the physical properties of soil. The "dispersion ratio" was obtained by dividing the amount of silt and clay in a sediment sample by the total quantity of silt plus clay present in the soil, and the "erosion ratio" was obtained by dividing the dispersion ratio by the colloid moisture equivalent ratio (which is, the percentage of water retained by a sample of soil one centimeter deep that has been saturated with water and drained under a centrifugal force 1000 times gravity for 30 minutes). He concluded that the greater its dispersion and erosion ratios, the greater the erosion of a soil. Based on these criteria soils have been divided according to erodibility and nonerodibility as follows:

(1) If "dispersion ratio" is greater than 10 and "erosion ratio" is greater than 15, soil is erodible.

(2) If "dispersion ratio" is less than 10 and "erosion ratio" is less than 15, the soil is nonerodible.

2.1.4. Vegetative Cover

Plant cover is one of the best protections against soil loss. Plant cover affects both the infiltration rate and the susceptibility of soil to erosion. It causes the absorption of raindrop impact and the reduction of overland flow velocity and tractive force by increasing the hydraulic roughness and decreasing the effective slope (Baver, 1965).

Mulches and vegetation increase the hydraulic roughness, and decrease the effective slope steepness, therefore, they reduce the runoff velocity and erosion. The effect of crops and their management cannot be evaluated independently. A crop can be grown continuously or in rotations. The sequences of crops within a system can be varied, and therefore, different combinations of these variables might have different effects on soil loss.

2.1.5. Human Factors

Most of the erosion control and conservation practices may be considered as human factors. Human beings disturb the soil, manipulate the vegetation and change the natural sequence of evolution. The legislative and administrative erosion control measures are the most effective means of preventing soil erosion or reducing it.

Beasly (1974) explained major practices to prevent soil erosion. Contour tillage, contour strip-cropping, and terracing with contour farming are among them. He indicated that terracing with contour farming is the most effective because with terracing, the sediment deposits in the terrace channel and may equal up to 90 percent of all the soil moved to the channel. Other practices such as diversion waterways, ponds, reservoirs, check dams, and gully control structures also may be considered as technical and engineering measures.

2.2. Overland Flow

Overland flow formulation and solution has been of great interest to engineering communities and the reported methods are divided into three groups; regression models, frequency analysis, and physical processes models (Linsley, 1971).

The use of hydraulic procedures for predicting overland flow is associated with some problems. Overland flow depends on rainfall supply which can be depleted by infiltration. Since both of these elements vary with time and location, the overland flow could be both unsteady and spatially varied. Depending on the rate of flow and nature of land surface the flow could be laminar, turbulent, or both. The impact of raindrop and formation of roll waves provide an additional complication in overland flow (Robertson et al., 1964).

There are many factors affecting the volume of water obtained from a rainfall or storm. These factors could be described as follows:

1. Rainfall characteristics
    a. rainfall intensity
    b. rainfall duration
    c. time distribution
    d. spatial distribution
2. Watershed characteristics
    a. watershed size
    b. watershed shape
    c. slope of watershed
    d. vegetative cover and its density
3. Soil characteristics
    a. shape

b. size distribution

c. unit weight

d. porosity

4. Climatic factor

a. temperature

b. wind direction

c. wind speed

d. antecedent moisture condition

5. Man-made factors

a. land use

b. construction.

As mentioned earlier, three types of overland flow formulation exist: regression models, frequency analysis, and physical processes. Regression models primarily attempt to establish a mathematical expression to relate rainfall to runoff. Frequency analysis uses statistical characteristics of the recorded rainfall or runoff to generate or synthesize nonrecorded events. Physical process models deal with the concept of water balance and divide the processes of rainfall and runoff into components (or parameters).

Overland flow and runoff transport the detached soil materials. Only when precipitation rate exceeds infiltration and all surface depression storage is exhausted will runoff occur.

Infiltration is defined as the rate at which water percolates into the soil. The equations presented in the literature describe the infiltration rate either by using the empirical concept (Horton, 1939; Holtan, 1961) or by equations based on the physical concept of water entry into the soil (Green and Ampt, 1911; Philip, 1957).

Horton's equation describes the exponential decrease of the infiltration rate. His equation is:

$$f = f_c + (f_o - f_c)e^{-kt} \qquad (2.4)$$

where;

f = infiltration rate (in/hr),

f_c = the infiltration rate assumed similar to the saturation permeability (in/hr),

f_o = the initial infiltration rate (in/hr),

t = time (hrs), and

k = a constant.

However, the difficulties with determining the parameters f_o and k cause this equation to be of lesser importance to the rainfall-runoff modeling of watershed.

Philip's (1957) infiltration equation is based on soil physics of water movement in porous media. The equation is:

$$I = S\ t^{1/2} + A\ t \tag{2.5}$$

where;

I = cumulative infiltration (in),

S = sorptivity which depends upon moisture content and diffusivity of the soil ($\text{in/sec}^{1/2}$),

A = a coefficient depending on conductivity at the wetting front (in/sec), and

t = time (sec).

Infiltration can be partially controlled by engineering and agricultural practices, such as tillage, raking of the surface, and compaction.

2.3. Soil Loss Determination

The soil erosion and consequently soil losses are among the important problems that engineering communities have been faced with during the last decades. The efforts of many researchers in predicting soil losses from farm land and agricultural watersheds have been reported since the 1930's. Zingg (1940) expressed soil loss as a function of slope length and steepness. The equation is:

$$X_e = 0.026(S_e)^{1.37}(L_e)^{1.60} \quad (2.6)$$

where;

X_e = total soil loss (lbs),

S_e = land slope in percentage, and

L_e horizontal length of land slope (ft).

Rainfall impact on the soil surface has long been considered the initial phase of the water erosion process. Ellison (1944) published an equation expressing soil erosion by splash as a function of raindrop size, velocity, and intensity. His equation is of the form:

$$E_s = R'(V_r)^{4.33}(d_r)^{1.07}(I_r)^{0.65} \quad (2.7)$$

where;

E_s = soil splashed in pounds during a 30-minute period,

R' = a constant,

V_r = raindrop velocity (ft/sec),

d_r = raindrop diameter (in), and

I_r = rainfall intensity (in/hr).

Musgrave (1947) found that the rate of sheet erosion was related to a number of factors and that certain relationships existed between these factors. He presented the following equation:

$$T_s = K_g(\bar{S}/10)^{1.35}(\bar{L}/72.5)^{0.35}(P_{30}/1.25)^{1.75} \quad (2.8)$$

where;

T_s = the probable soil loss (tons/acre/year),

K_g = a soil factor depending on the erodibility of soil and cover,

$\bar{S}$ = slope steepness (in percent),

$\bar{L}$ = slope length (in feet), and

P_{30} = the maximum 30-minute rainfall expected in a two year period.

Sheet erosion is not easily observed in the field because the irregularities on the soil surface cause minor rills to form. When these so-called micro channels form, they can be deepened and end as gullies. The significant erosion by the surface water would be within these channels. In scour erosion, rolling, lifting, and abrading of soil particles are the main process of soil detachment.

The studies of many researchers led to the development of Universal Soil Loss Equation (USLE). This equation (Wischmeier and Smith, 1965) is currently the most comprehensive and popular regression model to estimate soil loss. The Universal Soil Loss Equation is:

$$E = R\ K\ L\ S\ C\ P \tag{2.9}$$

where;

E = average annual soil loss (tons/acre),

R = the rainfall factor (the number of erosion index units in a normal year's rains),

K = soil erodibility factor (the erosion rate per unit of erosion index for a specific soil in cultivated continuous fallow on a 9 percent slope and 72.6 ft long),

L = slope length factor (the ratio of soil loss from a field for a given slope length to that from a 72.6 ft slope length on the same type and gradient),

S = slope-gradient factor (the ratio of soil loss from the field gradient to that from a 9 percent slope),

C = cropping-management factor (the ratio of soil loss from a field with specific cropping and management to that from the fallow condition on which the factor K is evaluated), and

P = erosion-control factor (the ratio of soil loss with contouring, strip-cropping, or terracing to that with straight row farming, up- and down-slope).

The Universal Soil Loss Equation was developed from more than 10,000 plot years of soil loss data. Usually, it is applied to farmlands because of massive amounts of data available for such areas. The USLE is not a complete sediment yield equation and does not include transport and deposition phenomenon of sediment yield. It is limited to annual soil loss for the entire watershed. However, the USLE has been used by Soil Conservation Service for many years.

Williams (1974) showed that erosion could be related to the transportation process more than the detachment process, and in order to characterize the transportation process, he used the volume and rate of runoff instead of rainfall factor. He proposed the Modified Universal Soil Loss Equation (MUSLE) in the form of:

$$E = 95(Q \cdot q_p)^{0.56}(K\ LS\ C\ P) \tag{2.10}$$

where;

E = sediment yield from an individual storm (tons),

Q = storm runoff volume (acre-feet),

q_p = peak runoff rate (cubic feet/sec),

K, L, S, C, and P are the same factors previously defined in the USLE.

In MUSLE a runoff factor composed of the runoff volume and peak runoff rate has been used instead of rainfall factor (R) in USLE. Williams (1974) found a close agreement between the predicted and measured data while using the MUSLE for computing the sediment yield for several different floods.

Foster et al. (1973) proposed a modified form of the USLE to reflect both rainfall and runoff contribution. This equation is:

$$E = E_n \, K \, C \, P \, L \, S \qquad (2.11)$$

where;

$E_n = 0.50 + 15 \, Q \, q_p^{1/3}$,

Q = runoff volume (in),

q_p = runoff rate (in/hr),

E, K. C, P, S, and L are the same as in the USLE.

One of the disadvantages of the regression type equations is that they are limited to their own particular data base and therefore restricted in application to those conditions and they lack a certain flexibility and could not interpret the physical process involving the soil erosion. Therefore, a need for improving the physical process modeling was apparent since all the above mentioned soil loss equations are typically based on regression analysis.

Meyer and Wischmeier (1969) subdivided the erosion process into four sub-processes. These are soil detachment by rainfall, transport by rainfall, detachment by runoff, and transport by runoff. They used the following mathematical models to evaluate each subprocess.

(1) Soil detachment by rainfall, D_r:

$$D_r = S_{Dr} A_i r^2 \tag{2.12}$$

(2) Transport by rainfall, T_r:

$$T_r = S_{Tr} S_o r \tag{2.13}$$

(3) Detachment by runoff, D_F:

$$D_F = S_{DF} A_i q^{2/3} S_o^{2/3} \tag{2.14}$$

(4) Soil transport by runoff, T_F:

$$T_F = S_{TF} q^{5/3} S_o^{5/3} \tag{2.15}$$

where;

A_i = the area of each increment (sq ft),

S_{Dr} = rainfall detachment factor,

S_{Tr} = rainfall transport factor,

S_{DF} = runoff detachment factor,

S_{TF} = runoff transport factor,

r = rainfall intensity (in/hr),

S_o = slope steepness, and

q = flow rate (cfs).

In fact, this was the first time that subprocesses of soil erosion were tied together in a mathematical form. The interaction between these four subprocesses determines the total erosion from each part of the watershed. The four submodels could be combined to route the soil downslope. The sediment load carried from each increment is the lesser of the sediment loads from the previous increment plus the detachment in that increment or the transport capacity from that increment. Net erosion for each increment is the difference between the sediment loads entering and leaving it. This conceptual model can be expressed in diagram form as shown in Figure 2.1.

Foster and Meyer (1972a) published the closed-form soil erosion equation. They derived this equation from basic hydraulic and sediment transport theory. According to their approach, the basic governing equation of the erosion process is the continuity equation for sediment transport which can be shown by the following formula:

$$\frac{\partial G_F}{\partial x} = D_F + R_{DT} \tag{2.16}$$

where;

G_F = sediment load in flow (wt/time/unit of cross section width),

x = distance along the flow surface,

D_F = flow detachment (wt/unit area/time), and

R_{DT} = rainfall detachment rate (wt/unit area/time).

The sign convention is: when $D_F > 0$ there is detachment, and when $D_F < 0$ there is deposition. An interrelationship between detachment by runoff and sediment load carried by runoff was given by:

$$\frac{D_F}{D_C} + \frac{G_F}{T_C} = 1 \tag{2.17}$$

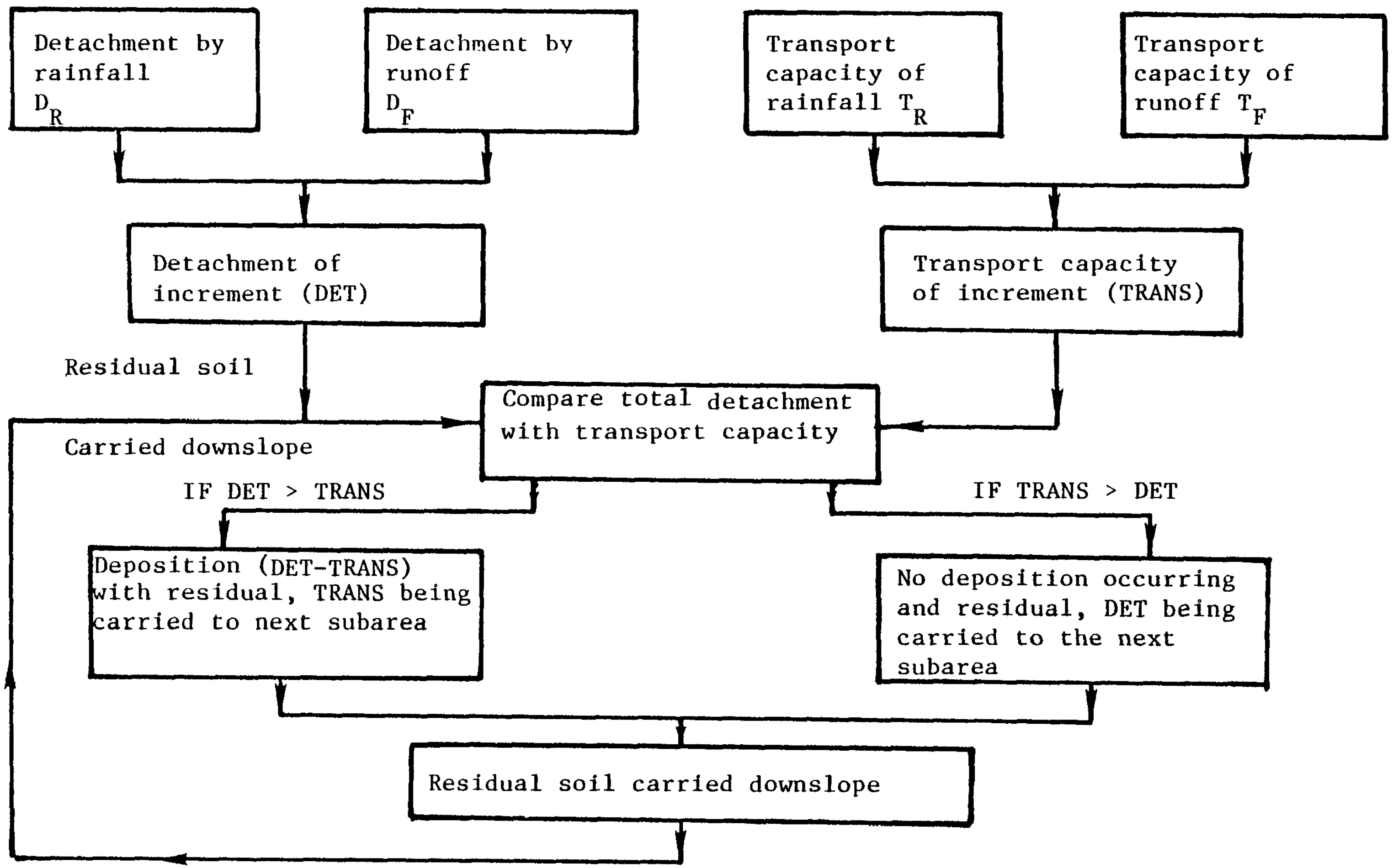


Figure 2.1. Simulation of soil erosion by water.

where;

D_C = the detachment capacity of the flow,

T_C = the transport capacity of the flow,

D_F and G_F were defined in the previous equation.

The terms D_C, T_C, and R_{DT} are independent variables defined by rainfall and runoff characteristics and by soil properties. Since rainfall and runoff both provide the energy required to detach and transport soil particles, the hydrologic process should be considered in the erosion simulation. Therefore, the important characteristics of rainfall and runoff were assumed either to be known or to be available from stochastic generation. Finally, the closed-form soil erosion equations were expressed as (Foster and Meyer, 1972a):

$$G_* = X_* - \frac{1}{\alpha} (1 - \theta)(1 - e^{-\alpha X_*}) \qquad (2.18)$$

and

$$A_Y = (G_*)(T_{co}) \qquad (2.19)$$

where;

$G_* = G_F/T_{co}$ = relative sediment load (dimensionless),

$X_* = x/L_o$ = relative distance (dimensionless),

$\alpha = L_o D_{co}/T_{co}$ = a flow erosion parameter (dimensionless),

$\theta = L_o R_{DT}/T_{co}$ = a rainfall erosion parameter (dimensionless),

A_Y = sediment yield (tons/ft/hr),

T_{co} = transport rate of flow at the end of a uniform slope (wt/unit width/time),

L_o = length of slope (ft), and

D_{co} = detachment capacity of flow at the end of a uniform slope (wt/unit area/time).

Foster and Wischmeier (1974) indicated that most equations were derived from data which was obtained from a uniform slope and they do not reflect the real phenomena of sediment movement. The effect of slope irregularity on sediment load is not accurately simulated by the overall average steepness. In relation to this fact and to detachment and transport capacity of soil erosion, Onstad and Foster (1975) have shown that the detachment capacity for any segment of a complex slope composed of uniform slope segments can be represented as follows:

$$D_{coj} = \frac{W_j(KCPS)}{185.58}(x_j^{1.5} - x_{j-1}^{1.5}) \qquad (2.20)$$

where;

D_{coj} = detachment capacity of flow at the end of a uniform slope segment j (wt/unit area/time),

W_j = an energy term for segment j (SI unit) = $0.50\ R_{st} + 15\ Q_j q_p^{1/3}$,

K = soil erodibility factor of USLE (tons/acre),

C = crop management factor of USLE (dimensionless),

P = soil conservation practice factor of USLE (dimensionless),

S = slope steepness factor of USLE (dimensionless),

x_j = distance from upper end of slope to lower end of segment j (feet),

x_{j-1} = distance from upper end of slope to upper end of segment j (feet),

R_{st} = storm rainfall factor of the USLE (Si unit),

Q = storm runoff volume (inches), and

q_p = storm peak runoff rate (in/hr).

Equation (2.20) shows that each segment may have a unique set of input parameters. Applying this concept to a watershed with complex slope having n segments, the following equation would result:

$$G = \sum_{j=1}^{n} D_{coj} \tag{2.21}$$

where;

G = the sediment yield of the slope.

They indicated that soil transport capacity is not the limiting factor. However, they used the USLE to analyze the transport capacity. The transport capacity (T_c) at any point x in lb/ft of width is:

$$T_c = \frac{W \bar{K} \text{ SCP } x^{1.5}}{185.58} \tag{2.22}$$

where;

W = average rainfall energy term (SI unit),

$\bar{K}$ = an average USLE soil erodibility weighted on the basis of contribution of each segment to sediment load.

After calculating the sediment yields and transport capacity at the bottom of each slope segment of a complex profile, if transport capacity exceeded the detached load of the segment plus any upstream contribution, the sediment yield was the sum of the detached load and the upstream contribution. Deposition did not occur on the segment.

However, if the transport capacity was less than the total soil available to be transported the sediment yield equaled the transport capacity and the rest of the soil was deposited on the segment. Calculations are carried out in this manner downslope to the channel was reached.

Kuh et al. (1976) used the aforementioned studies as input into a two dimensional model which can predict both the total amount of erosion from a watershed and areal distribution of erosion and sediment deposition. The end result was a map showing erosion or deposition in each grid on the watershed. Subsequently, iso-erodent lines were developed showing areas of erosion and deposition for one storm. However, they indicated that more research was needed for evaluating the flexibility of their model for use under different conditions.

Bennet (1974) presented a conceptual model to estimate sediment yield. The model divided the watershed into an upland and a lowland channel area. The concept of water continuity, momentum, and sediment continuity were used to formulate the erosion and sediment yield processes of both areas. The transporting capacity in the overland flow area and the channel systems, the variation of the channel bed, and the meandering of the channel system are considered to affect the rate of sediment transport and deposition.

Negev's (1967) model simulates generation and transport of soil by raindrop impact and overland flow. He presented the following formula for determining the production of fine soil particles by raindrop splash:

$$A(t) = (1 - FVC) \times K_n \times (P_t)^{AE} \qquad (2.23)$$

where;

A(t) = weight of soil particles produced during time interval t,

FVC = fraction of vegetative cover as a function of the relative value during the growing season,

K_n = the coefficient of soil properties (depending on the soil erodibility),

P_t = precipitation during the time interval t, and

AE = an exponent.

Fine particles which are produced are available for transport by overland flow. Depending on the transport capacity of flow these soil particles would be either removed or deposited. He modeled this process as follows:

$$SPT(t) = COT \times RDS(t - 1) \times OF(t)^{AN} \qquad (2.24)$$

where;

SPT(t) = soil particles transported during time interval t (weight), COT = coefficient of transport (depending on the transport ability of overland flow),

RDS(t - 1) = reservoir of deposited soil particles existing at the beginning of the time interval t,

OF(t) = the overland flow occurring during time interval t,

AN = an exponent.

David and Beer (1975) divided the erosion loss into rill and interrill contributions. They believed that in the interrill zone the soil erosion is mainly by the effect of raindrop splash. They proposed the following equation to determine interrill soil erosion.

$$E_d = (S_{cf})(L_{sf})(I_r)^z e^{-wd} \tag{2.25}$$

where;

E_d = erosion caused by raindrop splash (weight),

S_{cf} = soil cover factor,

L_{sf} = land slope factor,

I_r = rainfall intensity,

d = overland flow depth,

z and w = coefficients.

They indicated that in the rill zone, soil detachment is mainly by overland flow which takes place along the rill. The following equation describes this part of erosion:

$$E_r = C'd^u \tag{2.26}$$

where;

E_r = amount of rill flow scour (weight),

C' = a constant representing the soil characteristics and the overland flow surface slope,

d = the overland flow depth, and

u = a constant.

They indicated that the detached material that is not transported may be redeposited. These redeposited soil particles are left loosely on the ground as detachment storage until the next overland flow occurs. The following expression then describes the rate at which the total detachment storage decreases (David and Beer, 1975):

$$D_t = D_o e^{-Rt} \tag{2.27}$$

where;

D_t = total detachment storage at the end of the time interval,

D_o = total detachment storage at the beginning of the time interval,

$R = a_s/a_c$, where a_s is a soil related factor and a_c a climatic factor, and

t = the time interval.

Simons et al. (1975) developed a model to simulate the processes of erosion and sediment yield from a forested watershed. The mechanics of water and sediment routing, the effect of particle size on erosion rate and transporting capacity, and the processes of degradation and aggradation in the channel system were considered in their model. The governing equations were the water continuity, the momentum, and the sediment continuity equations. To solve the flow on land surface and in channels, kinematic wave approximation was used. Meyer-Peter, Muller's bed equation (1935) and Einstein's (1950) suspension procedure were used in computing the sediment transport capacity. Though this model appears to be very accurate, it requires large amounts of data and computer time to run. So, Simons et al. (1977) developed a single plane model which they call "physical process model." In that model instead of routing flow over time and space using finite difference formulations they average the physical processes over both time and space to obtain a simple approximation of the complex model.

The models or methods which have been discussed in this chapter are useful for predicting the soil erosion and sediment yield from a watershed. However, the advantages, disadvantages, limitations, and the applicability of them were not mentioned. Without the same sets of information to compute sediment yield for all of them, it is almost impossible to make comparisons. However, Shiao (1978) tried to classify them on the basis of their approach and theory. Table 2.1 shows this classification scheme. According to this table, the sediment yield models can be divided into three groups:

Group A - The Universal Soil Loss Equation (USLE) and its modifications. The models in this group were derived using a regression technique. During the years, some of these methods have been modified and their limitations developed to a certain degree. These techniques have been developed based on available data for specified areas, thus, the use of them for other areas creates some problems.

Group B - Those models use the concept of water continuity and balance the ratio of detachment and transport. The models are usually an improvement of the Group A type equations, since physical processes of soil erosion and sediment yield have been used in their formulations. Most of these models were developed on small areas or plots, and therefore their application is restricted.

Table 2.1. Classification of sediment yield models.

Group	Models
Group A	USLE (Wischmeier and Smith, 1965), Musgrave (1947), Williams (1975), Onstad and Foster (1975)
Group B	Meyer and Wischmeier's (1969) conceptual model, Foster and Meyer (1972), David and Beer (1975), Negev (1967)
Group C	Bennet (1974), Simon *et al*. (1975, 1977)

Group C - Those models with the complete processes of erosion and sediment yield. The models in this group are based on the physical and hydraulic processes of erosion and are usually more complex than other groups. The model described by Bennet (1974) is although only conceptual, is a good example as well as Simons _et al_. (1975) model which was tested with limited data.

SECTION 3

MODEL FORMULATION

3.1. Introduction

The processes of erosion and sediment yield are a complex physical phenomena. A mathematical model that attempts to predict soil erosion caused by rainfall is generally based on the fundamental factors involved in the erosion process.

In order to solve the complexity of the erosion process, the overall process must first be subdivided into several subprocesses that can be studied individually. In the development of this model, not all the physical processes of water erosion and sediment yield are included. However, an attempt has been made to develop a model that is logically sound, scientifically correct, practical, and uses easily obtainable data. This model has been called KEM and the Fortran Program listing along with an example is given in Appendix A and B. Some of the existing models are so complex that use of them is difficult and at times impossible because of the lack of available data.

Those processes which were considered in this model are presented in the following sections. However, it should be noted that the drainage area in this model is represented by 10,000 square sub-watersheds with homogeneous parameters, or by a square (100 x 100) matrix in computer format.

3.2. Physical Processes

Soil erosion is the result of two principal physical phenomena: the detachment of soil particles from the soil mass and the transport of these particles. The erosion process is possible if erosive agents are available. For water erosion, the area of interest of this research, the erosive agents are rainfall and runoff.

Raindrop impact is the primary source of energy for detaching soil from any land area. The impact breaks the soil aggregates into particles. Rainfall reaches the ground and percolates into the soil. If the subsoil is not saturated, the initial infiltration rate may be higher than the rainfall intensity, and the water penetrates into the soil. When the soil becomes saturated or the infiltration rate is less than the rainfall intensity, then water accumulates on the ground surface and begins to move by gravity as overland flow over the ground surface. If rainfall continues, the depth of overland flow increases and exerts a shear force, large enough to move the already loosened soil particles or erode soil from the ground surface.

Erosion begins at a place where the soil is most susceptible to erosion. Generally, if the binding forces of the soil particles are small, then erosion is more probable.

In general, runoff on erodible soil concentrates in many small channels. These microchannels are called rills, and the areas between the rills are then defined as interrill areas. The continuation of erosion processes, increases the rill dimensions and ultimately a gully will form. If the rainfall stops, or if it decreases, the transport capacity of the water is reduced significantly. Consequently, soil particles being transported by the runoff will be deposited as the runoff moves toward a stream or outlet point. Figure 3.1 shows the overall processes of erosion and sediment yield, and Figure 3.2 shows a typical rill cross section and its details.

Soil erosion from a watershed depends on many factors such as soil moisture, natural topography, vegetative cover, and the forces created by rainfall and the resulting runoff. Soils with a strong binding force such as clay are less likely to erode and soils with large particle sizes are more stable and therefore less likely to move. Slope also is a major factor, the flatter the slope the less susceptible the particles are to transport. Ground surface with dense vegetative cover not only reduce the detachment capacity of raindrop impact, but may retard the flow rates which consequently reduces the shear forces exerted by the flow. Figure 3.3 summarizes the factors influencing the soil erosion and sediment yield processes.

The structure of the model is presented in Figure 3.4. This model is formulated on the assumption that erosion process is divided into rill and interrill erosion according to sources of eroded sediment.

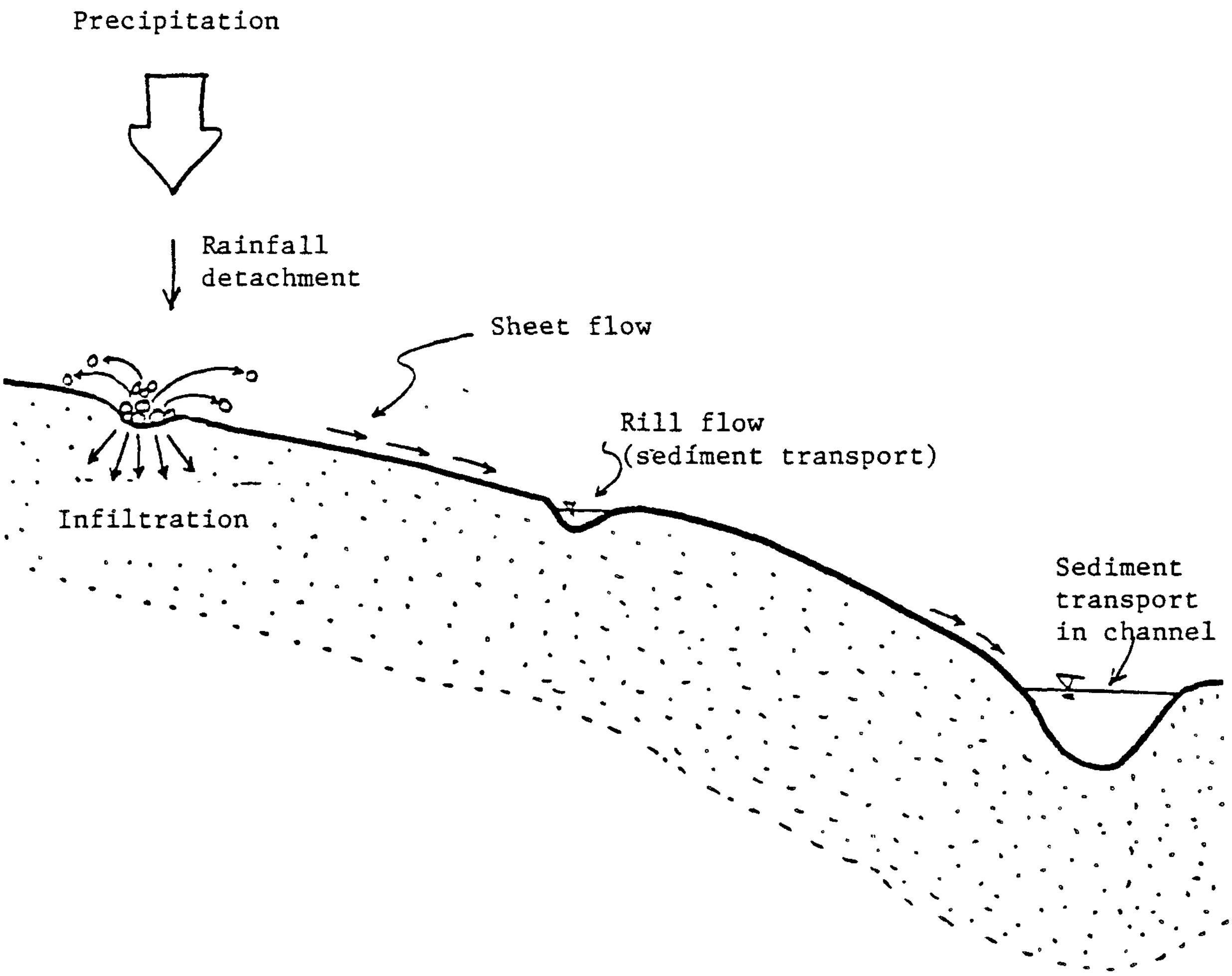
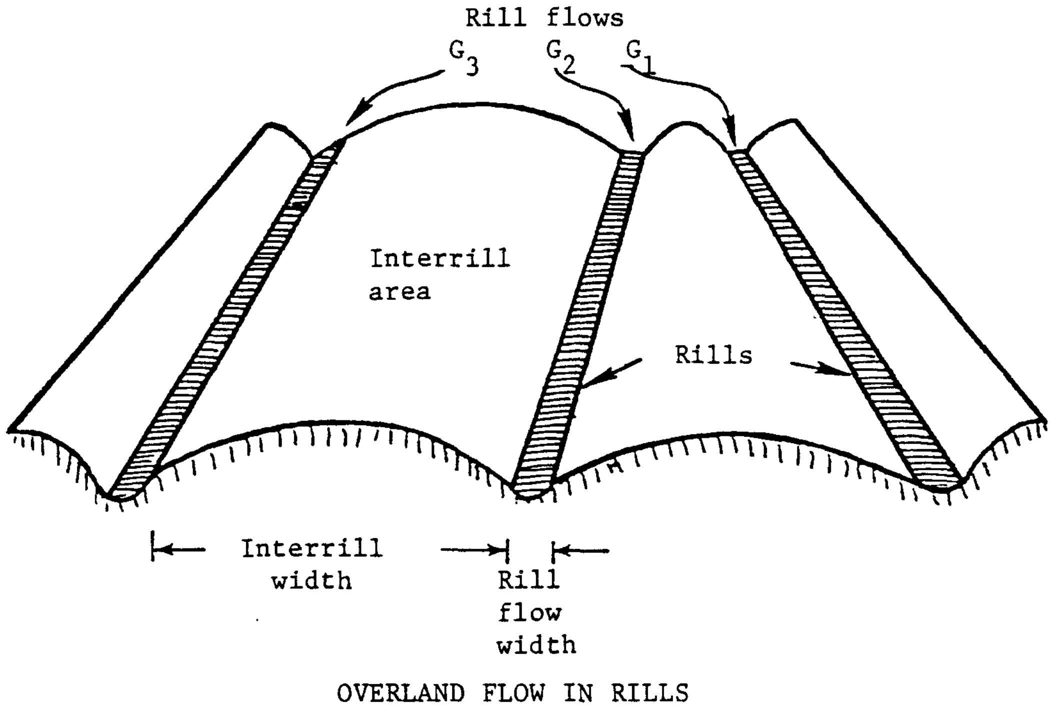


Figure 3.1. Overall processes of erosion and sediment yield.



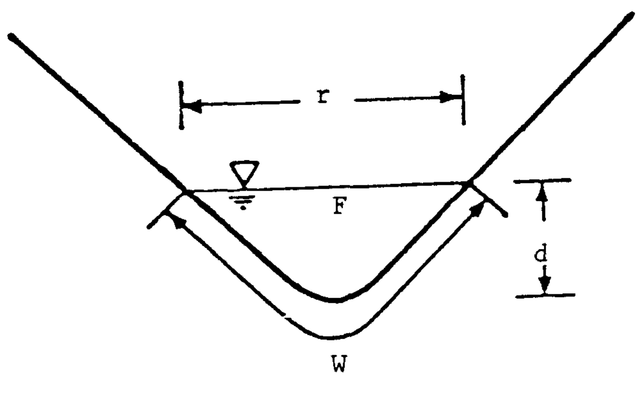


Figure 3.2. Interrill areas and rill details (triangular approximation for rill cross section).

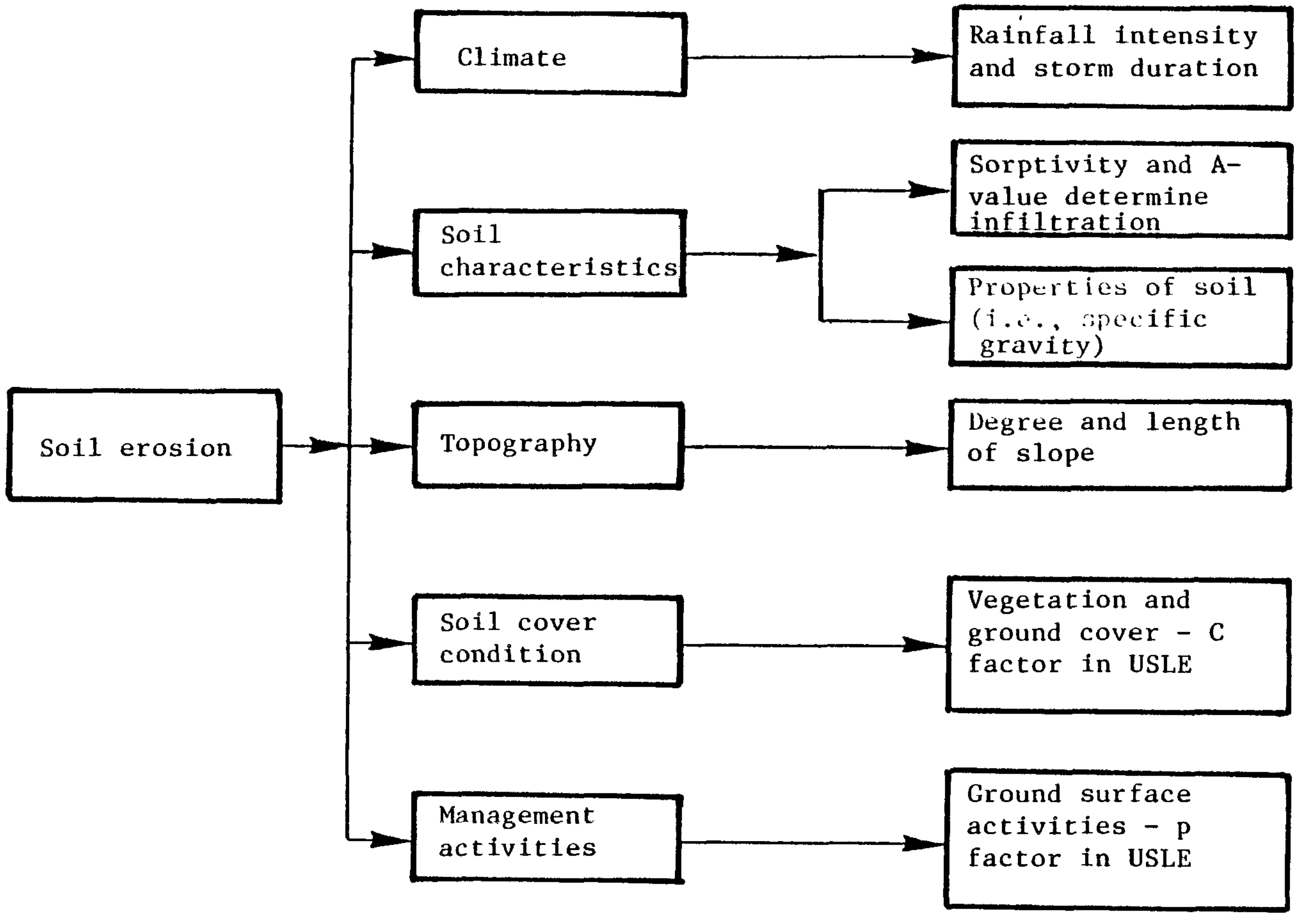


Figure 3.3. Factors influencing soil erosion in upland areas.

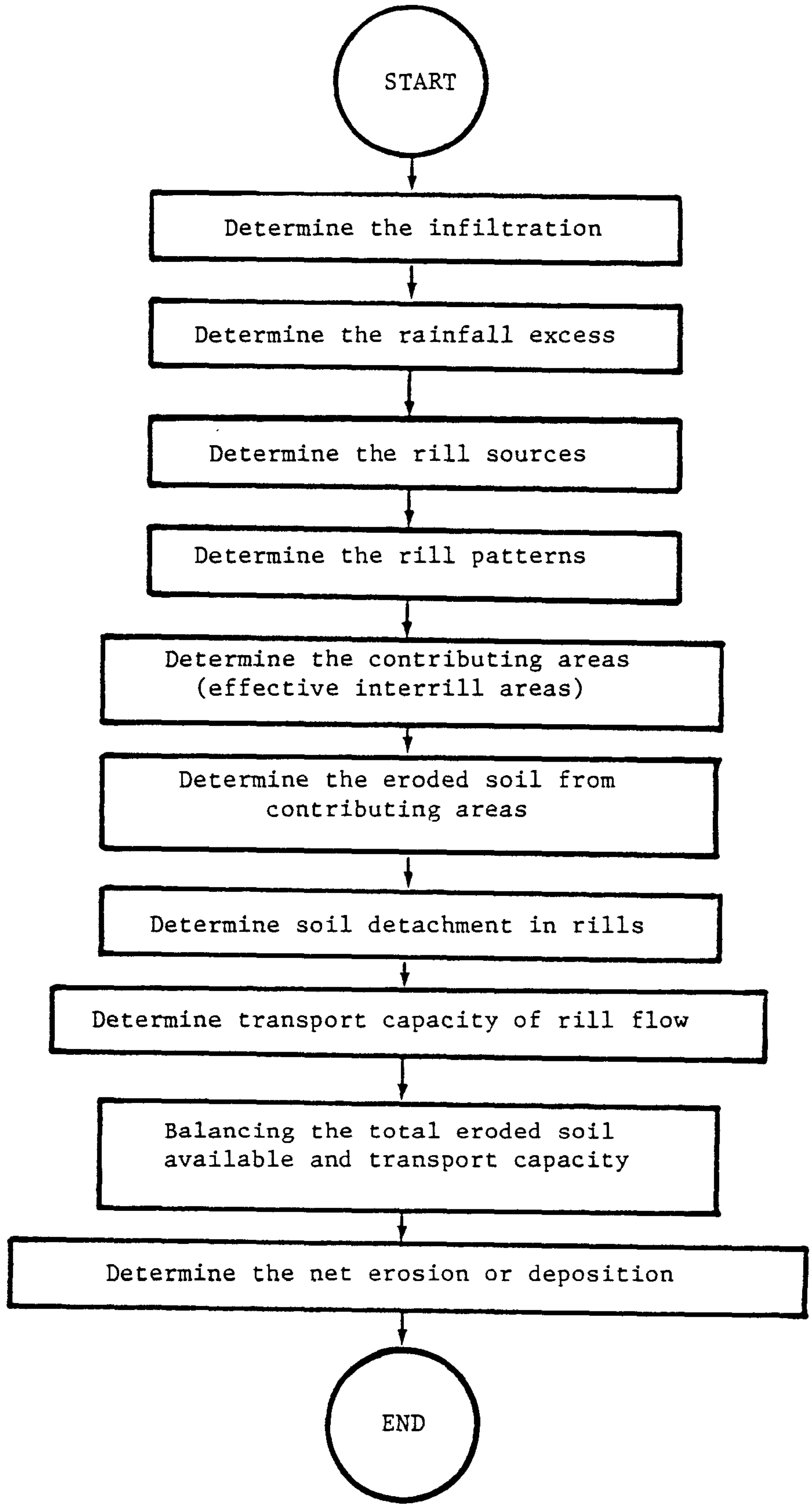


Figure 3.4. Structure of the model.

3.2.1. Hydrology Components

Rainfall and runoff can exert enough kinetic energy necessary to detach the soil particles from the ground surface. The amount of water available for the processes of erosion, and surface runoff, resulting from rainfall excess must first be determined. Rainfall excess is that amount of rainfall available after losses such as interception, depression storage, evapotranspiration, and infiltration have been subtracted. In this model, the losses due to interception, depression storage, and evapotranspiration are assumed to be negligible during storm periods and assumed to be included in the infiltration. The average rainfall intensity and steady state conditions are used for all calculations.

3.2.2. Infiltration

Infiltration is the movement of water into the soil. The infiltration process depends on surface condition, soil permeability, and soil moisture content. Several methods are available in the literature, to compute infiltration capacity (Horton, 1940; Green and Ampt, 1911; Philip, 1957). In this model, the cumulative infiltration is calculated by Philip's Equation. Philip (1957) derived an infiltration equation as follows:

$$I = St^{1/2} + At \tag{3.1}$$

where;

I = cumulative infiltration (in),

t = time (sec),

S = sorptivity of the soil (in/sec$^{1/2}$),

A = a parameter depending on soil water content (in/sec).

This equation gives the infiltration at a point. Since by definition each subwatershed is represented by a point, the equation is assumed to be applicable to this model.

Sorptivity of the soil (S) is of greater importance at short times in the beginning of infiltration, but A-value is of greater importance at long times. Rogowski's (1980) conclusion following his experimental evaluation of Philip's infiltration equation indicates that there is a poor correlation between the S and A values. The values of both S and A can however be measured experimentally (Tricker, 1978; Rogowski, 1980).

3.3. Model Description and Its Components

The impact of raindrops hitting the soil at a high velocity is the first step in the erosion process. Falling raindrops detach and transport soil particles. The transport capacity of rainfall depends on the slope of the land surface and on sloping land more than half of the detached soil by rainfall is moved downslope as it falls back to the surface. As rainfall continues, the infiltration rate decreases and consequently the rainfall excess begins. Thus, at first a thin sheet of surface runoff will form which is called sheet flow. Sheet flow can remove the lighter soil particles, organic matter, and soluble nutrients from the land. Also, sheet flow occurs rather uniformly over the surface and in some cases it may go unnoticed. The flow regime in sheet flow is considered to be laminar flow. If the surface were smooth and uniformly inclined, which is seldom the case, it is possible to have sheet flow. However, when the accumulated surface water moves downslope, it rarely moves as a uniform sheet flow over the land surface. Because, the land surface is usually irregular. Therefore, each portion of the surface runoff takes the path of least resistance, concentrating in depressions and gaining in velocity as the land slope and the runoff water depth increases. The flow regime is no longer laminar. The velocity of the runoff and its turbulence governs the erosiveness of overland flow. As the surface runoff increases, it is more likely that water will concentrate and sufficient soil may be removed to form small but well defined channels which are called rills.

3.3.1. Rill Sources

The initiation of rills can be described under two categories which depend on the subwatershed size.

3.3.1.a. Small Subwatersheds

The development of the rills is in fact a result of flow detachment. Concentration of overland flow (sheet flow) in rills and development of the rill pattern have not been extensively studied. Much of the published information concerning rill flow is directed toward predicting the detachment or erosion in the rills (Foster and Meyer, 1972). This is usually done by comparing the flow's average shear stress to the critical shear stress of the soil. However, it is clear that when rills start to develop, there should be enough energy associated with overland flow to develop a well defined path in an erodible soil. Since sheet flow is assumed to be a laminar flow regime and rill flow is a turbulent one, the distinction between these two flow regimes can be approximated in a mathematical way. Therefore, the initiation of rill depends on the following factors:

(1) The flow regime must be turbulent.

(2) The soil in that section must be erodible (soil erodibility factor, K, greater than or equal to 0.10).

(3) The slope steepness must be great enough to convey the water from the rill source.

The turbulence of the overland flow regime can be found from Reynold's Number. According to Venard (1961), if Reynold's Number is high (greater than 500), the flow regime is turbulent, otherwise the flow regime is laminar. The Reynold's Number is defined by Equation (3.2).

$$\text{Reynold's Number} = Vd/\nu \tag{3.2}$$

where;

V = velocity of surface flow (ft/sec),

d = depth of flow (ft), and

ν = kinetmatic viscosity (ft^2/sec).

The variation in kinematic viscosity due to temperature variation is shown in Figure 3.5. This is important because it may cause a 100 percent change in hydraulic conductivity (Shiao, 1978), which in turn might affect the permeability of soil and consequently the infiltration.

The above technique for finding the rill sources may not be considered suitable for all conditions. More specifically, when the size of subwatershed is small, this technique is more useful and more accurate in predicting rill sources. However, the degree of accuracy will decrease as the size of subwatershed (the horizontal and vertical distances between grid points) increases. For large subwatersheds, not only the data may not be very good, but the assumption that the subwatershed is

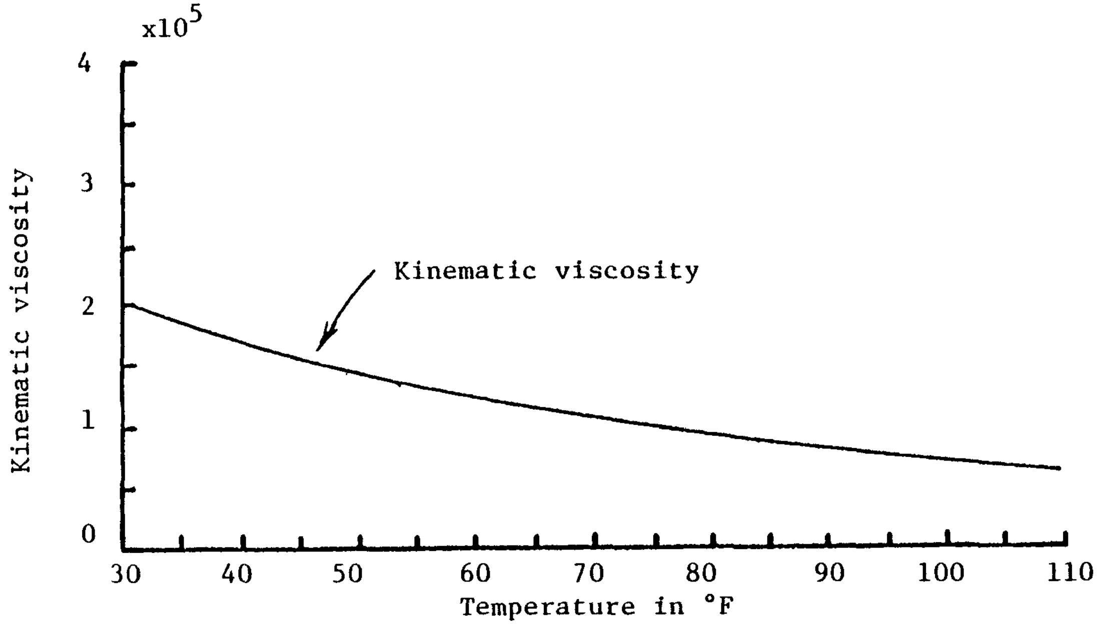


Figure 3.5. Variation of water viscosity with temperatures.

homogeneous and uniform may no longer be reasonable. The soil type may not be the same over the subwatershed area and the ground surface slope may not represent the details of slope steepness along the slope length. Rogowski et al. (1974) indicated that by decreasing length of slope length reading, more details of slope steepness for a fixed slope length can be obtained. To overcome these sources of errors, the following approach is considered to be more useful for larger size subwatersheds.

3.3.1.b. Large Subwatersheds

The rill source depends not only on rainfall properties, but is also influenced by infiltration. These two parameters are helpful to find the excess rainfall which is the main factor in determining rill source. The other important parameters are erodibility of soil and available positive slope. However, the suggestion is that a relationship between runoff-infiltration ratio and soil erodibility for developed rills can represent the conditions necessary in initiating rill formation. Figure 3.6 shows the role and magnitude of runoff-infiltration ratio and soil erodibility factor (K) in defining the rill source in this model. The region that runoff starts to concentrate as well as the one where the rill does not form have been indicated in Figure 3.6.

This type of curve, (Figure 3.6), is likely to be different for different states or regions of the United States. However, a

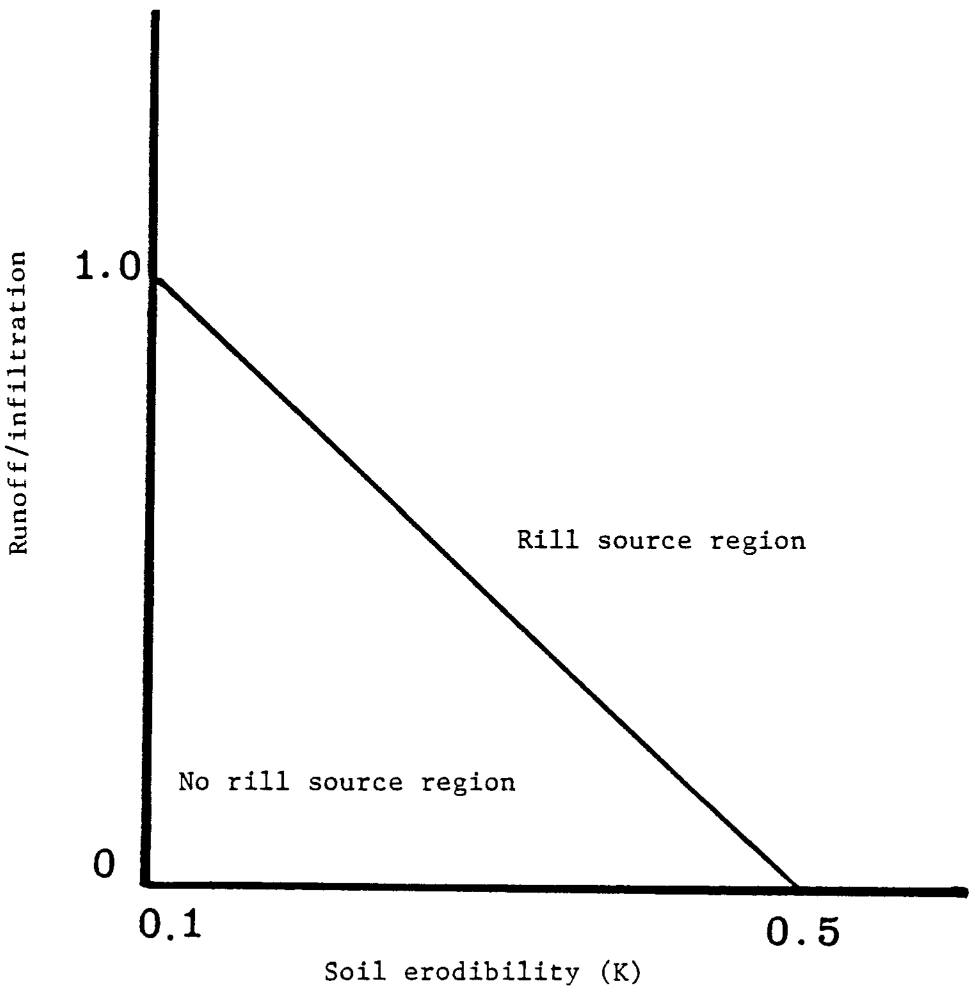


Figure 3.6. Influence of runoff/infiltration ratio and soil erodibility on rill source.

relationship between runoff-infiltration ration and soil erodibility factor for initiating the rill can be obtained experimentally or defined theoretically. In obtaining this type of graph, the permeability of soil may be assumed to be the ultimate infiltration rate. The necessary information for the graph can be obtained from soil maps and/or field measurements. However, in those areas which lack of available data, experimental techniques for measuring all the parameters are suggested. Based on Rogowski's (1974) result, it is recommended that if the width or length of subwatershed (grid point distance) is less than 30 feet the Reynold's Number approach works well, otherwise the second approach should be used.

3.3.2. Rill Development

The drainage area (watershed) is represented by 10,000 subwatersheds or a 100 by 100 matrix. The generation of rill patterns is done by a series of moves between adjacent points in the matrix. A rill consists of a series of connected, adjacent points in the matrix. Figure 3.7 shows a completed rill path.

Each rill starts from its source and ends up at the bottom of the watershed hillslope or joins an existing rill. Every point within the interior of the watershed is surrounded by eight other matrix points. These points represent possible directions of rill progression away from the source or previous point of rill (Figure 3.8). By assuming and judically picking the matrix orientation, the overall downhill

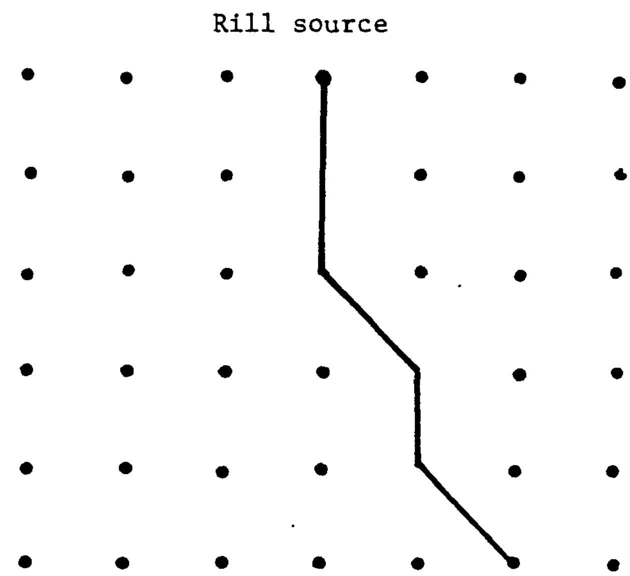


Figure 3.7. A rill path on watershed.

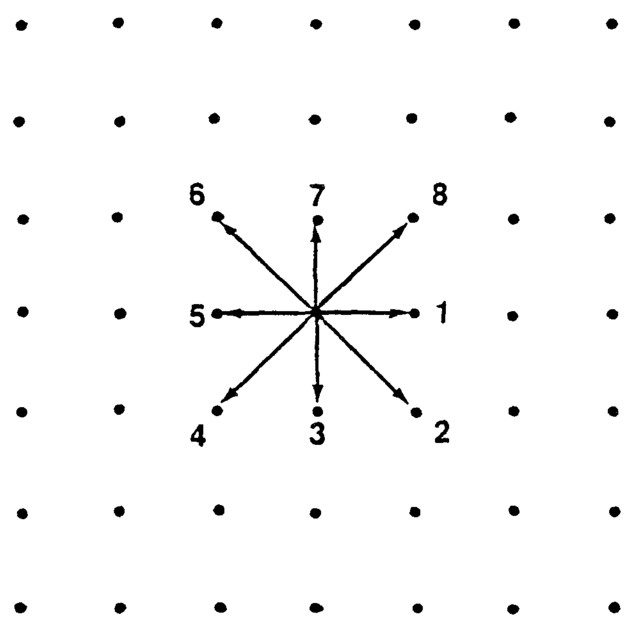


Figure 3.8. The possible directions of rill movement.

direction is from the top to the bottom of the matrix and thus there are only five possible step choices (Figure 3.9).

Therefore, as the rill pattern is developed downslope, each previously established point in the rill has to be connected to one of the five possible directions. The rill can move straight downslope, horizontally in either direction, or downslope at 45 degrees in either direction. The final path of rill is a sequence of moves from point to point in the matrix.

Since the rills are only affected by topography, the direction of each move is chosen by the steepest slope of all the five possible directions. The elevation of each point in the matrix and the horizontal distance between them are known. Therefore, slope steepness can be calculated as follows (see Figure 3.10):

$$S_1 = [E(k,l) - E(k,l + 1)]/L_1 \qquad (3.3a)$$

$$S_2 = [E(k,l) - E(k + 1,l + 1)]/L_2 \qquad (3.3b)$$

$$S_3 = [E(k,l) - E(k + 1, l)]/L_1 \qquad (3.3c)$$

$$S_4 = [E(k,l) - E(k + 1,l - 1)]/L_2 \qquad (3.3d)$$

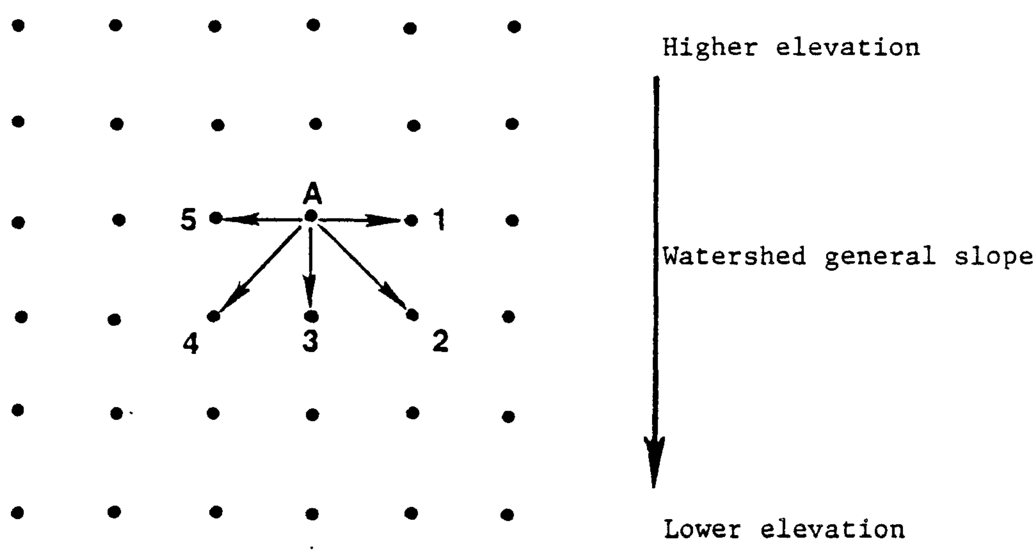


Figure 3.9. Five possible directions for rill movement at Point A.

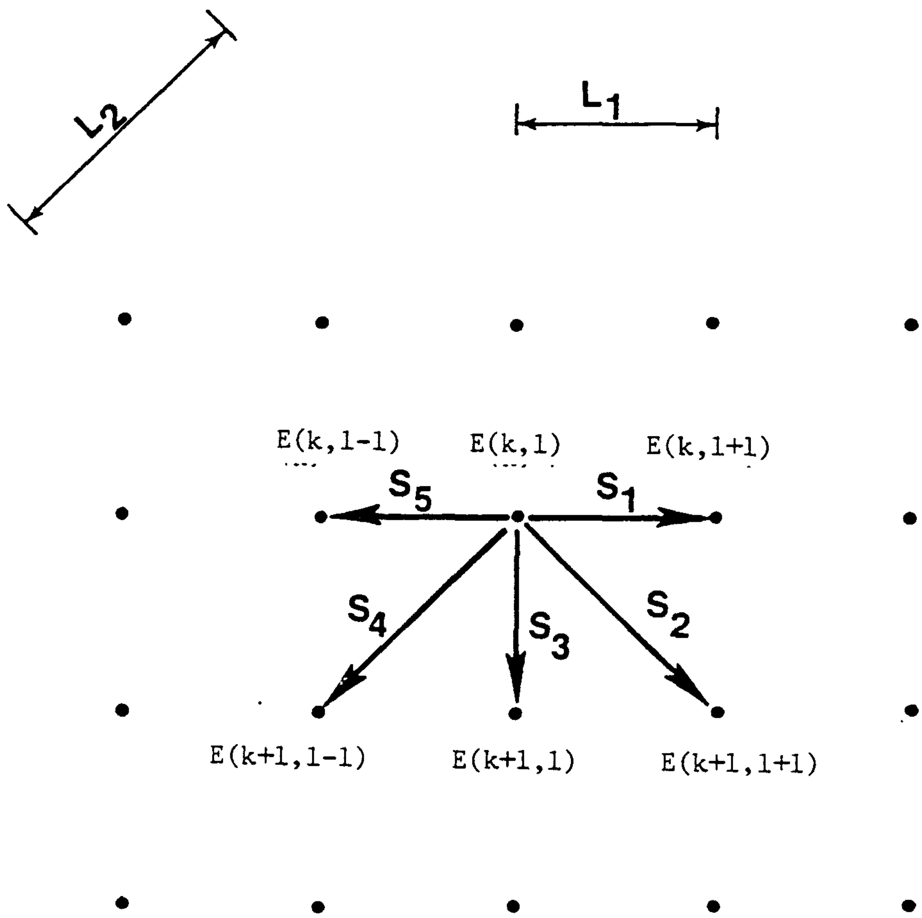


Figure 3.10. Slope steepness in the five possible rill directions.

$$S_5 = [E(k,l) - E(k, l - 1)]L/l \qquad (3.3e)$$

where;

E(k,l) = elevation of the point in the "k"th row and "l"th column,

L_1 = the horizontal and vertical distance between two adjacent points in the matrix,

L_2 = the distance between two adjacent points at 45° direction.

After completion of the first rill by moving from its source to the downslope boundary, the second rill path is developed. This process is repeated until all the rills have been generated.

There are several special cases in which the rill patrern is constrained. They are as follows:

(1) Rills are not allowed to exit at the side boundaries.

(2) If $S_1 = S_2$, S_2 would be selected.

(3) If $S_1 = S_2 = S_3$, S_3 would be selected.

(4) If $S_1 = S_2 = S_3 = S_4 = S_5$, S_3 would be selected.

3.3.3. Contributing Areas-Partial Area Concept

Most of the soil loss equations for prediction of erosion from irregular slopes were developed for estimating soil erosion for the entire watershed. The partial-area concept is a different approach. According to the concept of partial area hydrology, watershed areas do not produce surface runoff with uniform frequency. Therefore, only some portions of the watershed have high potential for surface runoff. These areas of the watershed are likely to be close to the rivers, gullies, or the small channels (rills), and those areas within a watershed with low potential for surface runoff or far away from the drainage system will be less likely to erode or if erosion occurs, there will be little or no sediment contribution to the flow system.

As mentioned earlier, rills are considered the only flow system capable of transporting the eroded soil. Therefore, according to the concept of partial-area hydrology, runoff in the rills is produced only from distinct portions of the watershed, in this case interrill areas, which are adjacent to the rills. These contributing areas are required to have surface runoff (sheet flow) to convey the eroded soil to rills. Therefore, all subwatersheds one node away from a rill could contribute to the rill. If the area contributes runoff (sheet flow), it is considered as the contributing area, otherwise, it is a non-contributing area.

3.3.4. Governing Equation

The watershed areas are divided between interrill areas and rill areas and different type of erosion mechanics are involved. Erosion occurring in rills is defined as rill erosion, and erosion occurring on the interrill areas is defined as interrill erosion.

Since soil erosion processes involve detachment and transport of soil material by rainfall and runoff, the mechanics of soil erosion is composed of four subprocesses described by Meyer and Wischmeier (1969). These processes as described earlier in Chapter 2 are: detachment by rainfall, transport by rainfall, detachment by runoff, and transport by runoff. However, depending on the watershed characteristics, some of these subprocesses may be negligible.

It has been assumed here that interrill erosion is mainly due to detachment by rainfall and transport capacity of rainfall is only high enough to carry the detached soil material from the interrill areas to rills. According to this assumption, rills are the only overland flow system responsible for carrying the interrill detached soils to the downslope of watershed and ultimately the watershed outlet.

Young and Wiersma (1973) determined the relative importance of raindrop impact and overland flow on the erosion process. In their laboratory study they used soils with three textures: loam, silt loam, and sandy loam. They used simulated rainfall with preformed rills in a 5 ft x 15 ft plot bed. They concluded that for all three type soils tested, 80-85% of the soil loss originating in the interrill areas was transported to rills before leaving the plot. Therefore, although rainfall impact is primarily responsible for soil detachment in interrill areas, the rill flow is the main transport mechanism of the detached particles. However, the rill flow also contributes soil erosion and this must be added to interrill material. Their result supports the assumption for this model.

The total detached soil material in the rills is then compared to the sediment transport capacity to determine if sediment will deposit or if all of the material will be transported to the next node. The routing procedure is done for all segments of the rills from upslope to downslope of the watershed.

The basic governing equation of the erosion process in this model is the continuity equation for sediment transport. This equation is as follows (Foster and Meyer, 1972):

$$\frac{\partial G}{\partial X} = D_r + D_i \qquad (3.4)$$

where:

G = sediment load (weight/time/unit of rill width),

X = distance downslope along the rill paths,

D_r = detachment (or deposition) rate of rill erosion (weight/time/unit of total area, including rill and interrill areas), and

D_i = delivery rate of particles detached by interrill erosion to rill flow (weight/time/unit of total area).

The above equation can be explained as a mass balance technique for each rill path. The following sections describe different equations and techniques that are used to model the interrill areas and the rill system.

3.3.4.a. Interrill Erosion

The dominant factor in the detachment of soil particles on interrill areas is considered to be raindrop impact. Raindrop impact and the sheet flow associated with the excess rainfall on the interrill areas transport the detached soil particles from the effective (contributing) interrill areas to the small flow channels (rills). Because the depths and flow rates on interrill areas are small, the shear stress due to the thin sheet flow is small and almost no detachment occurs. Therefore, the detachment capacity of sheet flow in interrill areas can be neglected. Thus, interrill erosion is primarily due to soil detachment by raindrop impact and subsequent transport of the detached particles by shallow interrill sheet flow.

After specifying the contributing interrill areas which contribute erosion and runoff to rills, the amount of erosion from these areas would be calculated. The Universal Soil Loss Equation (USLE) is the most common estimator of annual potential soil loss caused by rainfall.

The equation expresses annual soil loss per unit area due to erosion by rainfall which is the only dominate erosive agent in interrill areas. The USLE was formulated by Wischmeier and Smith (1965) as:

$$E = (R)(K)(LS)(C)(P) \tag{3.5}$$

where;

E = computed annual soil loss (tons/acre),

R = rainfall energy factor,

K = soil erodibility factor,

LS = slope-length factor,

C = cropping management (vegetative cover) factor, and

P = erosion control practice factor.

This equation is generally for large watersheds. However, it was applied successfully to small watersheds by Rogowski and Tamura (1970) and should be applicable for each subwatershed in this model.

One of the important factors in the Universal Soil Loss Equation is the rainfall energy factor (R). R-values (Wischmeier and Smith, 1978) normally used in the USLE for annual values of erosion do not apply to individual storms. Cooley (1980) presented a more general equation relating maximum 30-minute intensity for storms of any duration and volume of total precipitation. His equation provides R-values for individual storm events of the four storm types defined by the Soil Conservation Service (SCS Technical Notes, June, 1970). These storm types represent typical rainfall distribution used in hydrologic studies. Cooley's Equation is of the form:

$$R = \frac{a\ J^{Y}}{D^{b}} \tag{3.6}$$

where;

$Y = 2.119\ D^{0.00086}$,

R = rainfall energy factor,

J = total storm rainfall in inches,

D = storm duration in hours,

a and b = constants depending on the storm type.

The values of a and b are obtained (Cooley, 1980) and Table 3.1 presents these values to be used in Equation (3.6).

The LS factor in the Universal Soil Loss Equation represents the effects of slope length and slope steepness. The general magnitudes of the LS factor can be estimated as follows (Wischmeier and Smith, 1965):

Table 3.1. Values of a and b in Equation (3.6) for each SCS storm type[1].

SCS Storm Type	Coefficients a	Coefficients b
IA	12.98	0.7488
I	15.03	0.5780
II	17.90	0.4134
IIA	21.51	0.2811

[1]Cooley (1980).

$$LS = (L)^{0.5}[0.0076 + 0.0054(S) + 0.00076(S)^2] \qquad (3.7)$$

where;

L = length in foot from the point of origin of the overland flow to the point at which runoff enters a defined channel, and

S = the average slope over the runoff length (in percent).

The soil characteristics affecting raindrop impact detachment are difficult to quantify. They vary with time and wetting of the soil and formation of a surface seal affect them. Due to the difficulty to obtain the tested parameter of these factors, the soil erodibility factor in the Universal Soil Loss Equation may be the best available indicator of the relation between raindrop impact and the soil properties controlling detachability.

According to Foster and Meyer (1975), the transport capacity of interrill flow is a function of several factors. Some of these factors can be mentioned as runoff rate (sheet flow rate), slope steepness, roughness of the ground surface, transportability of detached soil particles, and effect of raindrop impact. However, Podmore and Merva (1971) indicate the thin sheet flow on the interrill areas without the raindrop impact is probably able to transport only a small load. The raindrop impact significantly increases the transport capacity on the interrill areas. In this model, it is assumed that all the detached soil from the contributing interrill areas, based on the concept of partial-area hydrology, is transported to the rills. The following section explains how this transport does occur mathematically.

3.3.4.b. Contributions to a Rill

The soil particles eroded in the contributing interrill areas would be transported to rill joints. The steepest slope of the contributing interrill area to the adjacent rill joint governs where the sediment enters the rill. Since rills are assumed to be the only flow system that carries surface runoff, the excess rainfall (sheet flow) from contributing interrill areas would also be transported to rill joints in the same way as the interrill erosion. After completion of these processes, there would be two numbers corresponding to each rill: one representing the total runoff and other the total eroded soil available. The next task will be to route the runoff and sediment from rill source through rill path. However, the detachment capacity and the transport capacity of rill flow would have to be taken into consideration.

3.3.5. Governing Equations in Rills

The sediment routing procedure in this model is based on two processes: Balancing the sediment supply rate and the transport capacity of rill flow. The available eroded soil from the contributing areas is added to the soil detachment in rills and the total is compared to the transport capacity of rills. If the total eroded soil is greater than total transport capacity of rill flow, only that portion of eroded soil that can be transported by the flow would be transported to the next section of a rill. If the total eroded soil is less than rill transport capacity, all the eroded soil would be transported by rill flow.

3.3.5.a. Rill Cross Section

To route runoff and sediment, it is necessary to estimate the rill cross section. However, to be able to achieve this goal, other parameters need to be found first. One of these parameters which is used to determine the flow rate in each rill section is the travel time between rill joints.

The time that it takes for runoff to travel from one joint in a rill to the next joint is called the travel time for that section of rill. It depends on the rill length, land slope steepness (or rill bed slope for pre-existing rills), and soil roughness. Depending on the available information, there are several methods for finding the surface flow time between two joints (points) of a rill. Since one of the objectives of this study was to develop a simple model with readily available data, the equation recommended by Federal Aviation Agency (1970) was used to compute travel time. The equation is:

$$T = \frac{1.8(1.1-y)\sqrt{L}}{\sqrt[3]{S}} \tag{3.7}$$

where;

T = surface flow time or travel time (min),

L = length of flow path (ft),

S = slope of flow path (in percent),

y = a composite weighted factor (always less than one).

The value for y factor in the above equation is equal to the C factor in Rational Formula (R = CIA) of hydrology. However, if this factor is not known other approximations are applicable. In this model, the value of the factor is approximated by the volume of runoff divided by the volume of rainfall.

The rate of flow in the rill (Q) is found by dividing total runoff at that section of rill by the travel time. Although rills are small channels, they can be considered hydraulically as open channels. For uniform flow in open channel system the common Manning's Formula is valid. This equation is:

$$Q = \frac{1.49}{n} (H)^{2/3}(SS)^{1/2}(F) = VF \tag{3.8}$$

where;

Q = flow rate in the rill (cubic feet per second),

F = flow cross sectional area (square feet),

n = Manning's roughness coefficient for rill,

H = hydraulic radius defined as flow cross sectional area divided by the wetted perimeter (feet) = F/W

SS = slope of the energy gradient (under steady state, it equals the slope of rill bed),

V = mean velocity of rill flow (ft/sec).

Manning's roughness coefficient, especially for shallow depth, depends on flow depth. According to the available data (Beasley, 1974; Ree and Palmer, 1949), the following equation is recommended for calculating the value of n for rills which are considered to be shallow channel systems in bare soil. The equation is:

$$n = 0.018 + 0.01(d) \qquad (3.9)$$

where;

n = Manning's roughness coefficient,

d = flow length in rills (ft).

It was assumed that rill cross sections have a triangular shape with the bed sides perpendicular to each other (Figure 3.2). Therefore, hydraulic radius (H) and rill cross section area (F) can be expressed in terms of flow depth (d).

$$F = d^2 \tag{3.10}$$

$$H = F/W = (d^2)/2\sqrt{2}\,d) = 0.3535\ d \tag{3.11}$$

Substituting Equations (3.9) and (3.11) in Equation (3.8) results in the following equation:

$$0.745(SS)^{1/2}(d)^{8/3} - 0.01(Q)(d) - 0.018(Q) = 0 \tag{3.12}$$

where;

SS = slope steepness,

d = rill flow depth (ft), and

Q = rill flow rate (cfs).

In order to solve Equation (3.12) for d, Newton's approach (Carnahan, 1969) is used. Knowing d, the flow depth in the rill, the velocity of flow and width of rill can be computed.

3.3.5.b. Rill Transport Capacity

Meyer and Wischmeier (1969) illustrated their approach for finding the runoff transport capacity by an equation of the form:

$$T_f = S_{tf}(SS)^{5/3}(Q)^{5/3} \qquad (3.13)$$

where;

T_f = runoff transport capacity,

S_{tf} = a coefficient depending on the soil's transportability properties,

SS = slope of the energy gradient of flow, and

Q = flow rate.

Since the coefficient (S_{tf}) is not sufficiently evaluated yet, Yalin's Equation (1963) is recommended. Yalin's Equation is applicable based on the assumption used for its derivation. The equation assumes that sediment motion begins when the lift force of flow exceeds a critical lift force. After a particle is lifted from the bed, it would be in suspension until it settles back to bed by gravity force. The concepts in the Yalin Equation seem most applicable to conditions of concentrated shallow flow associated with upland erosion. The

Yalin Equation requires only two common flow parameters, hydraulic radius and slope of the energy gradient. The transportability of a soil depends on the particle density, particle diameter, and the critical lift force. The Yalin Equation is:

$$T_f = 0.635(SG)\rho_w m(SV)g\delta[1 - \frac{1}{\sigma}\log(1 + \sigma)] \quad (3.14)$$

where;

$$\sigma = h \cdot \delta \quad (3.14a)$$

$$\delta = (T - T_{cr})/T_{cr} \text{ (when } T < T_{cr}, \delta = 0) \quad (3.14b)$$

$$h = 2.45(SG)^{-0.4}(T_{cr})^{0.5} \quad (3.14c)$$

$$T = (SV)^2/(SG - 1.0)gm \quad (3.14d)$$

$$SV = \sqrt{gH(SS)} \quad (3.14e)$$

T_f = transport capacity of rill flow (lbs of sediment/second/ ft. of flow width),

SV = shear velocity of flow (ft/sec),

g = acceleration of gravity (ft/sec^2),

ρ_w = mass density of the fluid,

H = hydraulic radius (ft),

SS = slope steepness,

SG = particle density,

m = soil particle diameter (ft),

T_{cr} = critical lift force, which is given in the Shields diagram (Figure 3.11).

To obtain the critical lift force (T_{cr}), the size of soil particle is required to use Shields diagram. Since the particle size in the rill bed is not included in the input data of this model, it has to be generated. The soil particle size can be found by relating it to Manning's roughness coefficient. This relationship is (Shen, 1971):

$$n = 0.034(m)^{1/6} \tag{3.15}$$

where;

n = Manning's roughness coefficient,

m = particle diameter (ft).

In order to find the critical lift force (T_{cr}), Shields diagram was recommended by Yalin to be used in Equation (3.14b) and Equation (3.14c). However, the Modified Shields diagram (Shen, 1971) is used

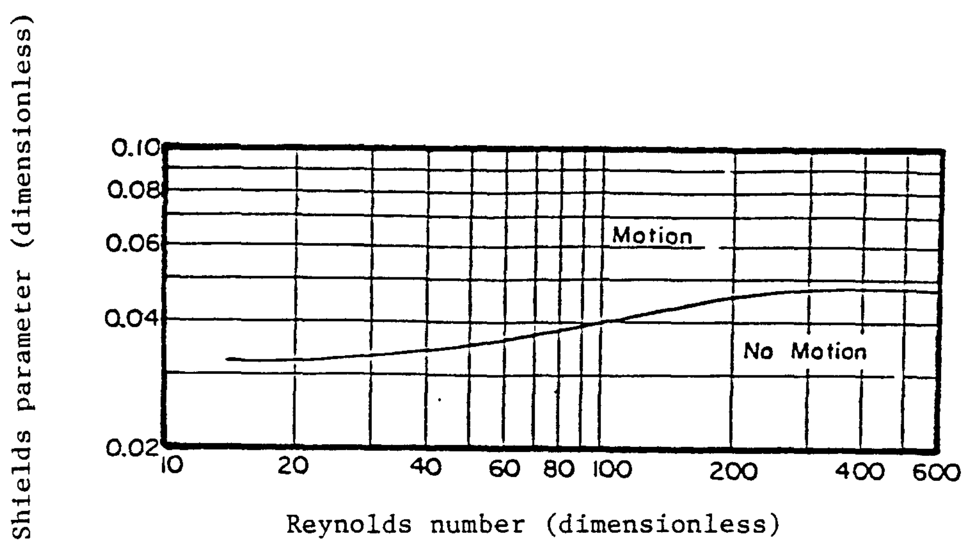


Figure 3.11. Shields diagram.

here since it is easier to use in a computer model. Figure 3.12 presents the Modified Shields diagram. This graph can be approximated to fit a straight line with the following equation:

$$Z = \frac{1}{13.2} U^{0.92} \qquad (3.16)$$

where;

$$Z = \tau_{cr} \left[\frac{1}{\nu^2 (\gamma_s - \gamma_w)^2 \rho_w} \right]^{1/3} \qquad (3.16a)$$

$$U = m[(\gamma_s - \gamma_w)/\rho_w \nu^2]^{1/3} \qquad (3.16b)$$

ν = kinematic viscosity of flow (Figure 3.5),

γ_w and γ_s = specific weight of rill flow and soil, respectively, (lb/ft^3),

τ_{cr} = critical shear stress (lb/ft^2),

m = soil particle diameter (ft),

ρ_w = mass density of the rill flow which is assumed to be equal to that of water.

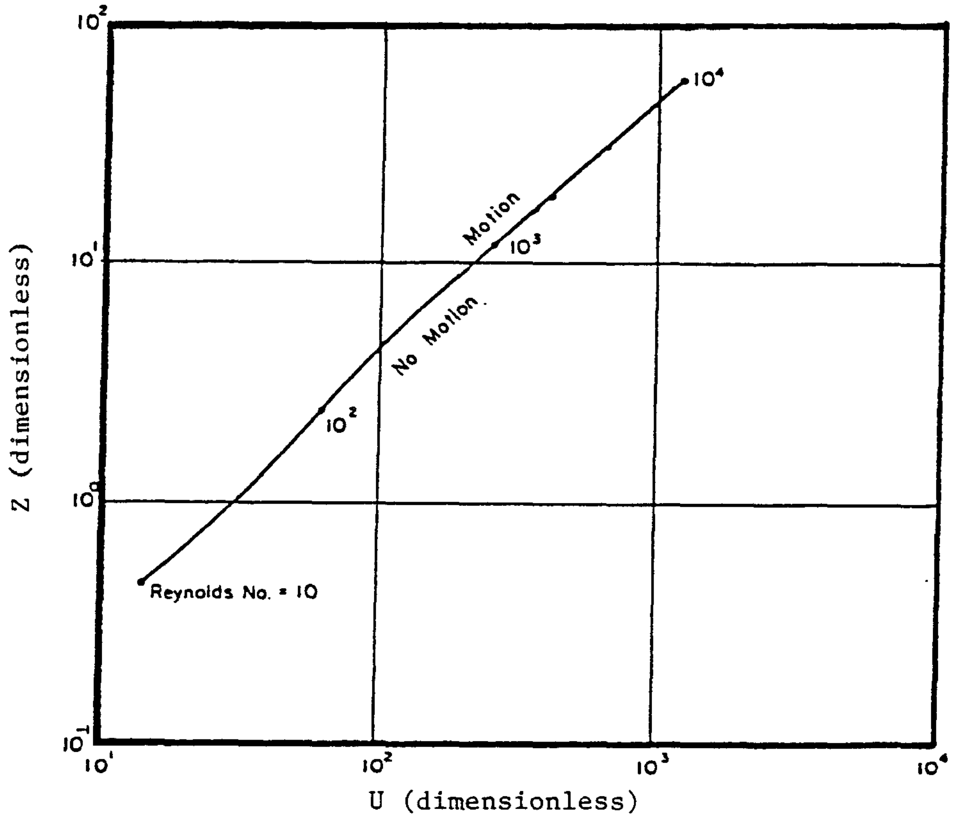


Figure 3.12. Modified Shields diagram.

3.3.5.c. Rill Detachment Capacity

The detachment capacity of rill flow is defined as the rate per unit of total area at which rill flow without a sediment load can erode particles from the soil matrix at a location on the slope. The detachment capacity of rill flow (D_c) depends strongly on the average bed shear. It is taken as proportional to a power of the difference between actual shear stress and a critical shear stress. The critical shear stress is believed to be the minimum requirement for initiation of motion of sediment grains in the rill bed. A possible expression for detachment capacity of rill flow (D_c) is (DuBoy, 1879):

$$D_c = C_c(\tau - \tau_{cr})^{\alpha} \tag{3.17}$$

where;

D_c = detachment capacity of rill flow (weight/time),

τ_{cr} = critical shear stress (lb/ft^2),

τ = actual shear stress (lb/ft^2),

C_c and α coefficients depending on the soil and fluid properties.

Applying the DuBoy's type formula to narrow channel and neglecting the channel side effects lead us to the following equation (Morris and Wiggert, 1971):

$$g_s = \frac{D_c}{B} = \psi\,\tau(\tau - \tau_{cr}) \qquad (3.18)$$

where;

g_s = detachment capacity (bed load in lb per ft of width per time),

B = rill width (ft),

γ = specific weight of fluid (lb/ft^3),

G/s = total detachment (lbs of bed load), and

ψ = a sediment characteristic factor.

The value of ψ is found to be:

$$\psi = \frac{10\,V}{m(\gamma_s - \gamma)} \qquad (3.18a)$$

where;

γ_s = specific weight of the bed material (lb/ft^3),

V = flow velocity in rill (ft/sec), and

m = sediment particle diameter (ft).

Knowing the particle size of sediment material, critical shear stress (τ_{cr}) can be found from Shields diagram or Modified Shields diagram (represented by Equation 3.16).

All the rill segments would then be routed using equations and techniques discussed above. The result would be a net amount of soil accumulated at each joint of rill. By comparing it with the eroded soil before the start of runoff, the erosion or deposition at each joint would be obtained.

3.4. Data Requirements

Data needed for this model can be divided into two categories: field data and model input data. Field data includes, contour map, soil properties, vegetation distribution, ground cover characteristics and rainfall distribution. Model input consists of data obtained from maps that have been converted to conform to the format requirements for the model.

Soil characteristic maps are difficult to obtain. However, SCS maps usually contain most of the needed information. The vegetation distribution map is generally difficult to find for a natural watershed, but a field trip may yield required information. For larger watershed aerial surveys and land satellite information are useful. Rainfall data is usually recorded near or at the site.

The model input includes three types of information: climatological, watershed geometry, and watershed physical characteristics.

Climatological data include rainfall intensity, duration, and average temperature at the beginning of the storm. Watershed geometry data consists of slopes and watershed dimension while watershed physical characteristics data include soil characteristics, vegetation type, and cover conditions.

SECTION 4

APPLICATION OF THE MODEL AND RESULTS

4.1. Introduction

To test the applicability of the model, it was applied to a watershed and the results obtained were compared with experimental data. The flow diagram of the input-output files is shown in Figure 4.1. The information about the watershed and the procedure used to obtain the input data and to choose the model parameters are described in the following sections.

4.2. The Study Area

An area selected to test the model is a 10 acre watershed in Central Pennsylvania described in detail by Pedersen *et al*. (1978). This stripmined and reclaimed land is adjacent to undisturbed land. The site is located less than a mile northeast of Kylertown in Clearfield County, Pennsylvania. Figure 4.2 shows the general location of the site. It lies within the Pittsburgh Plateau section of the Appalachian Plateau Province. The geologic system is Pennsylvanian, characterized by cyclic sequences of sandstone, shale, coal, and clay (Pedersen *et al*., 1978). The north most part of the area was reclaimed

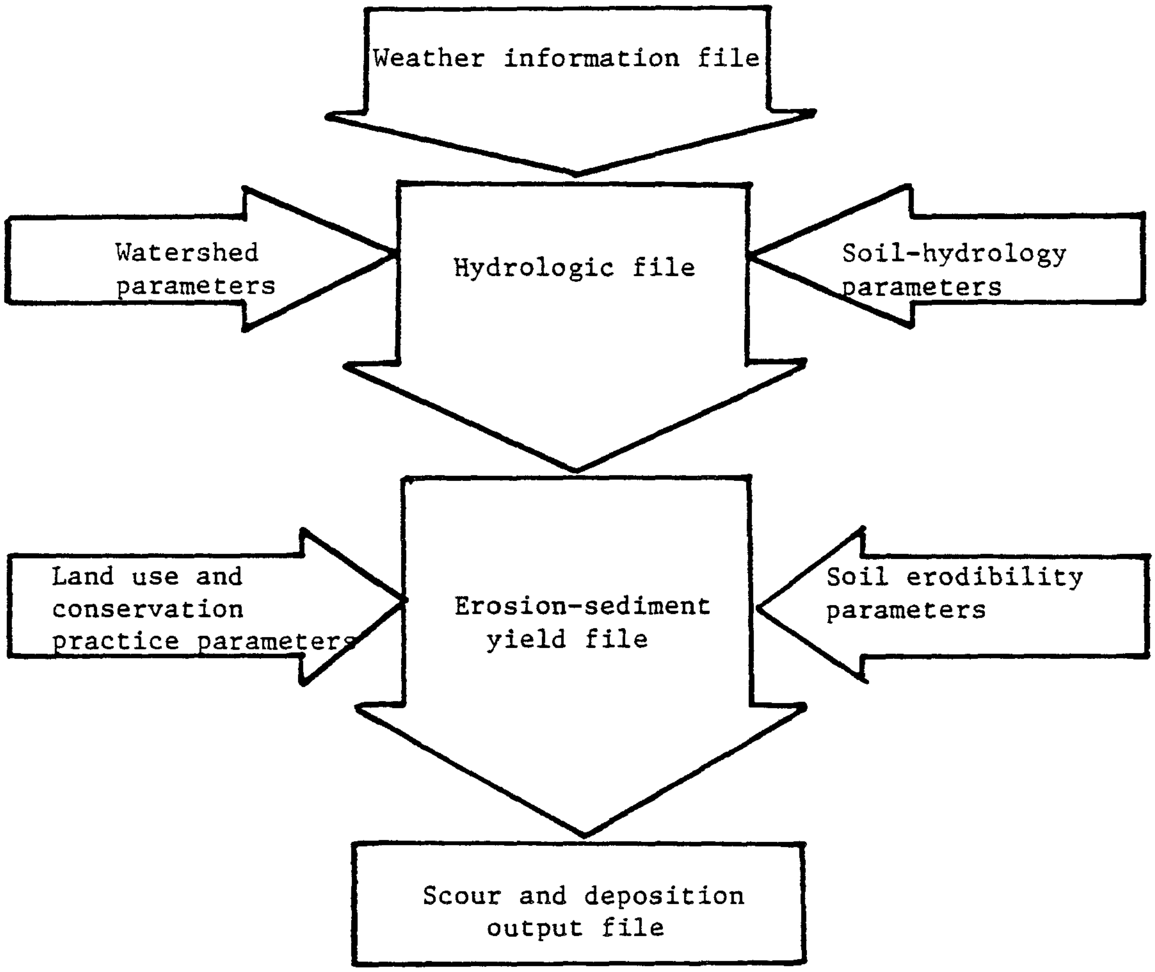


Figure 4.1. Flow diagram for the input-output files.

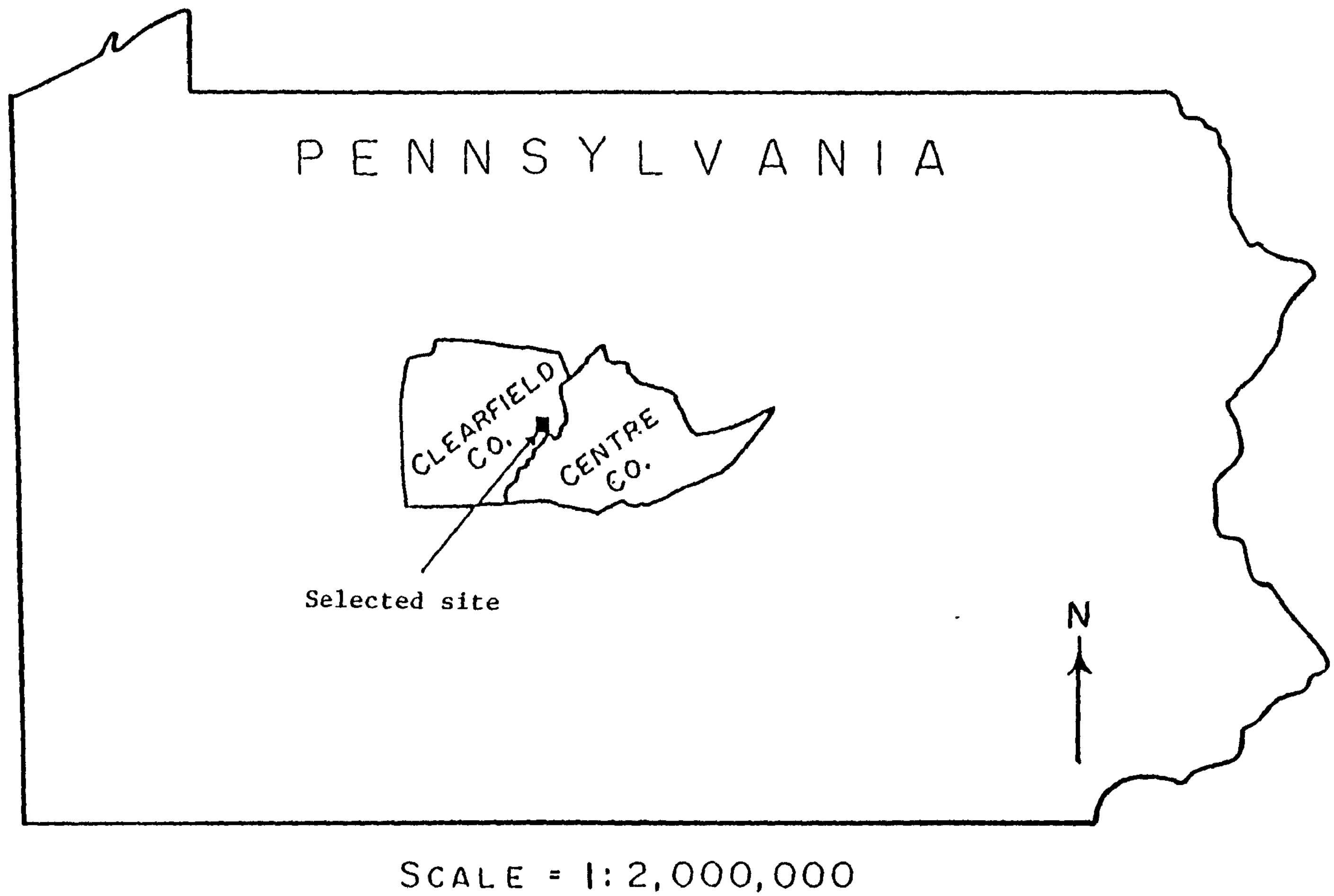


Figure 4.2. The location of the study area.

in 1969 and the south most reclaimed and topsoiled in 1974 (Rogowski, 1980). On the periphery of the topsoiled and nontopsoiled areas are small pockets of undisturbed soil (Rogowski, 1980).

To test the erosion model, a 460 ft x 320 ft portion ABDC (Figure 4.3) of the site was selected because it has all the parameters necessary for numerical simulation of erosion. The required data were measured from instruments located at the site for the past few years (Pedersen et al., 1978; Rogowski, 1980).

4.3. Input Data

The important parameters and variables determined prior to application of the model are summarized in the following sections.

4.3.1. Topography

Topography of the site was obtained from the field survey and is shown in Figure 4.4. Although this figure presents four foot contour intervals, two foot contour intervals has been used in this study for better accuracy.

4.3.2. Infiltration Parameters

To determine the runoff available for transport of eroded sediment estimates of infiltration were needed. Rogowski (1980) used the

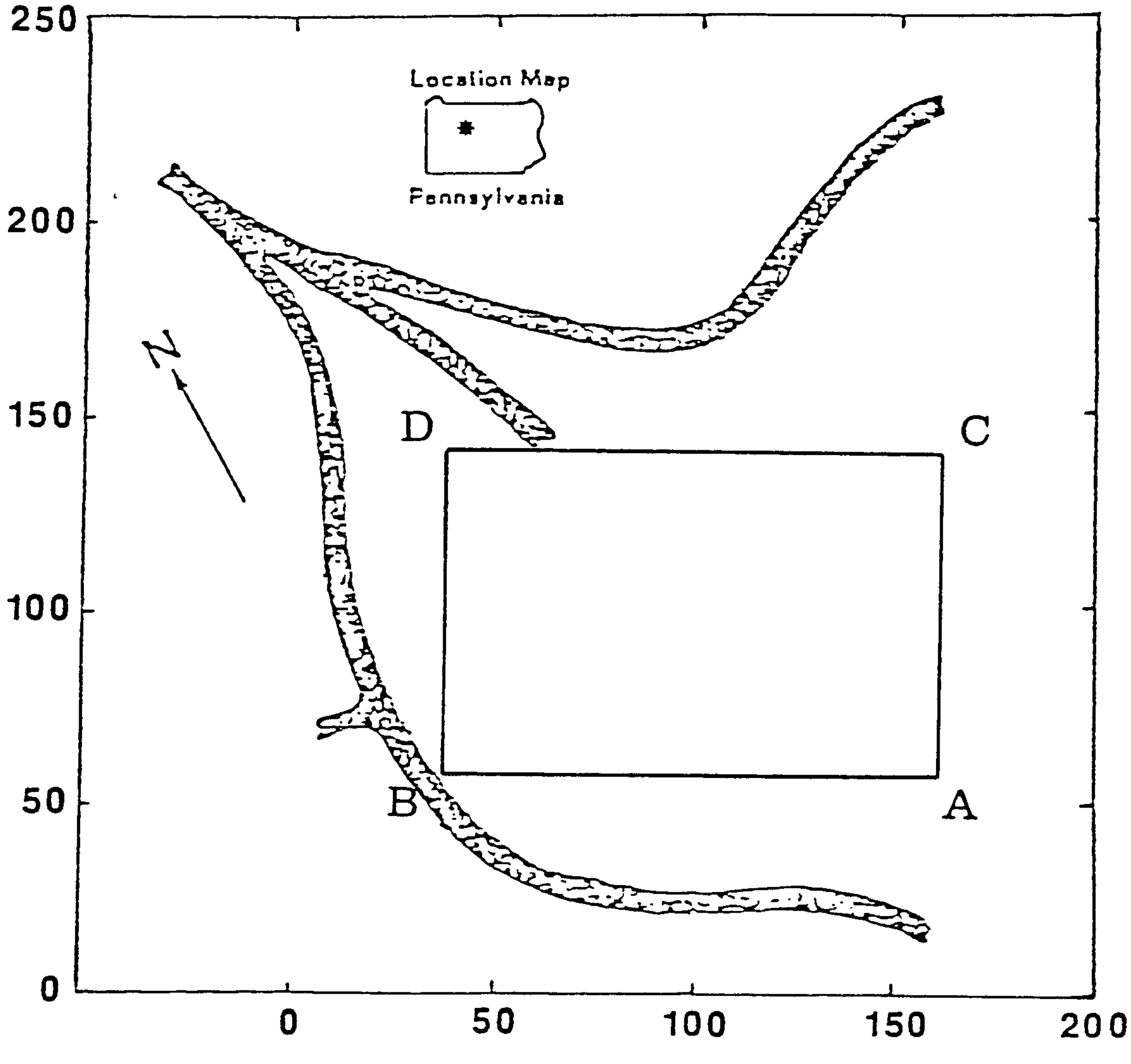


Figure 4.3. Location of area ABDC in the selected watershed. (Note: The numbers are relative coordinates to be matched with Figures 4.5, 4.6, 4.9, and 4.16).

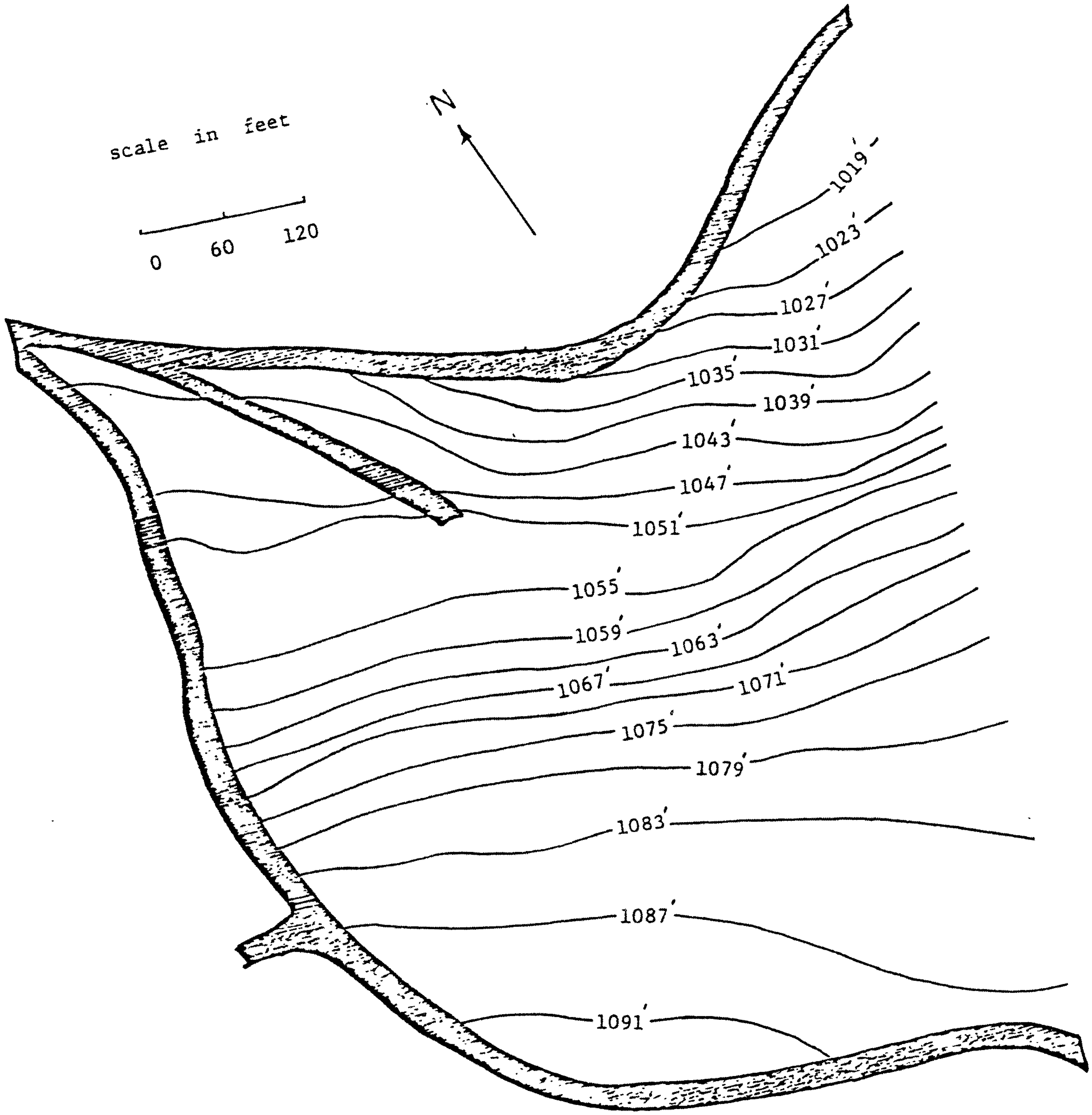


Figure 4.4. Topography of the selected watershed.

same site for an experimental study of infiltration on mine spoil. He measured the infiltration rates and obtained the infiltration parameters (S and A values for Philip's (1957) equation, Equation 3.1). These parameters (shown in Figures 4.5 and 4.6) were used to compute infiltration over the area during the study period (June 1 to September 1, 1981).

To obtain these values, Rogowski (1980) used ring infiltrometers. In this method, the measured infiltration rate may exceed the true rate if the flow penetrates below the bottom of the ring. Depending on the ring diameter, the measured infiltration rate can be off by 16 to 34 percent. Tricker (1978) in his study indicated that this error can be appropriately corrected. His correction equation for small ring (6 inches in diameter) which has the larger error can, assuming uniform permeability and air-dry soil, be written as:

$$I_c = 0.65\ I_m^{0.46}\ t^{-0.64} \tag{4.1}$$

where;

I_c = corrected infiltration rate (in/hr),

I_m = measured infiltration rate (in/hr), and

t = the cumulative time (hrs).

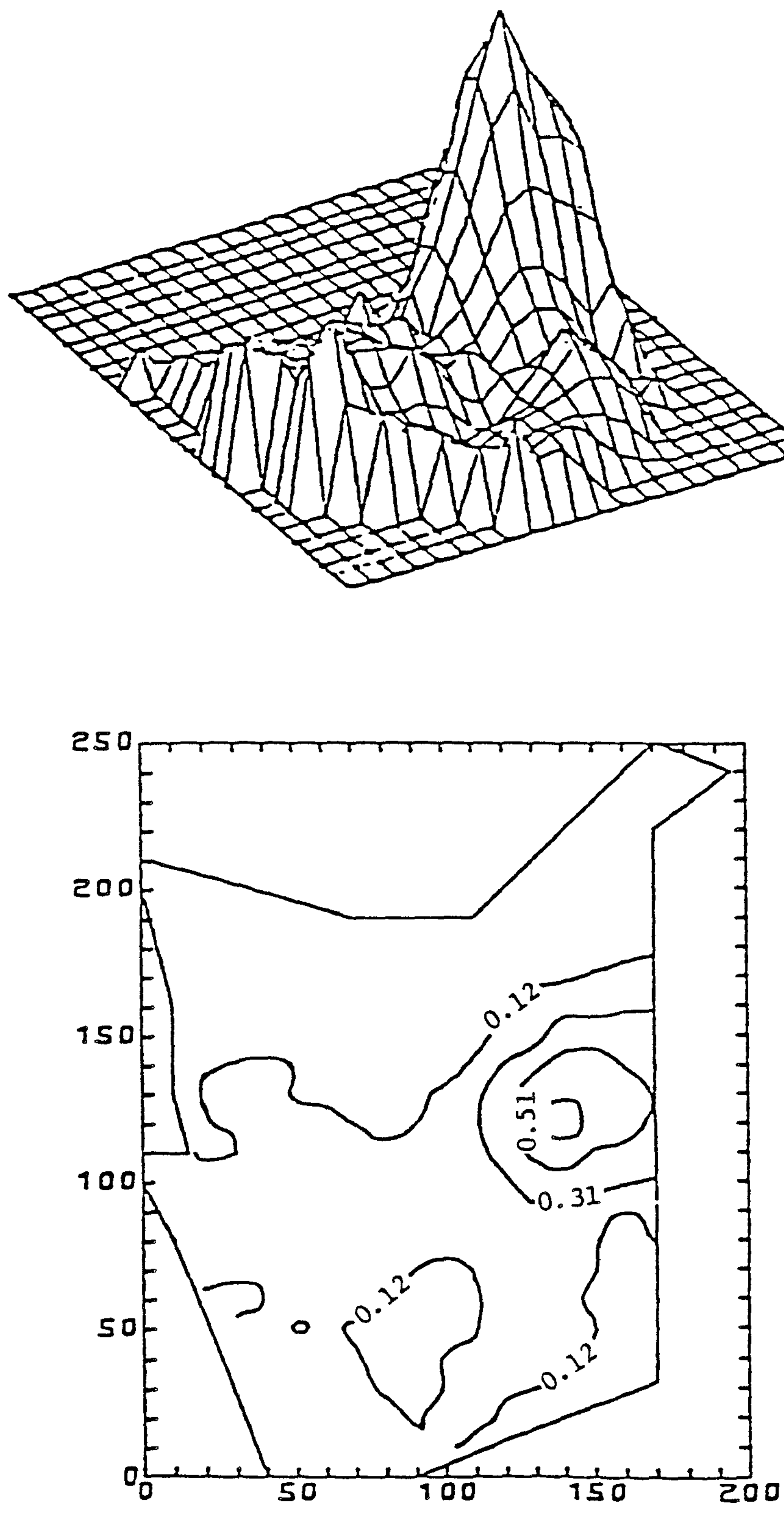


Figure 4.5. Soil sorptivity (in/sec$^{1/2}$) of the selected watershed, in three and two dimensions.

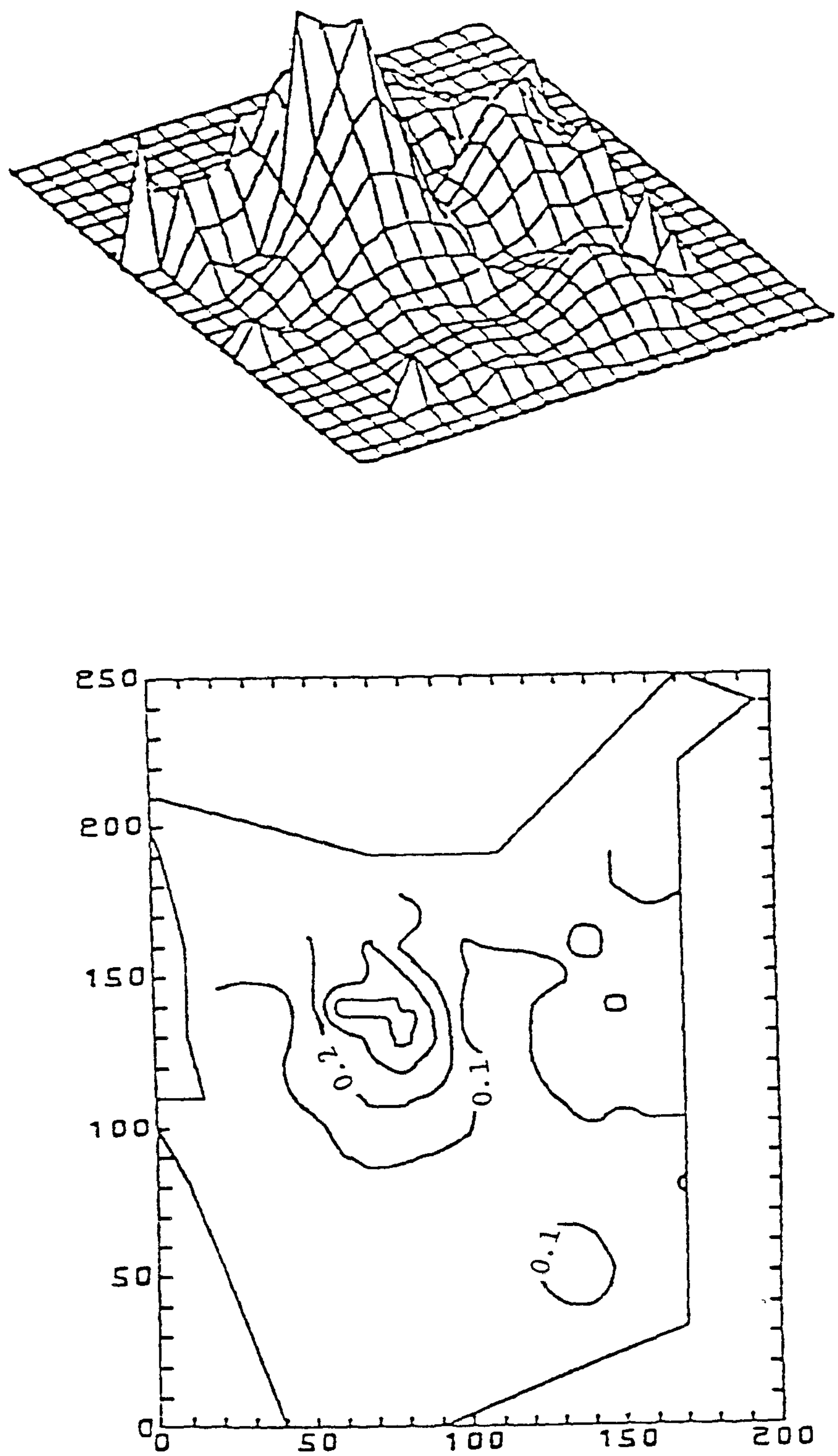


Figure 4.6. A-values (in/sec) for the selected watershed, three and two dimensions.

This correction seems to give better results for longer times where largest errors occur (Rogowski, 1980). Therefore, this equation was incorporated into the model to correct the experimental infiltration rate.

4.3.3. Precipitation

Precipitation was measured by a universal rain gage. Table 4.1 presents the storm events which occurred in Summer 1981 (June 1 to September 1). According to Soil Conservation Service (SCS Technical Note, June 1970), there are four types of storm events which represent a range of rainfall distributions commonly seen in hydrologic studies. Figure 4.7 shows these distributions and illustrates the storm types and their distribution observed during the study period. To evaluate the storm type dominant at the site, the distribution of these storm events is plotted in Figure 4.7 and their characteristics are presented in Table 4.1. Because of the short duration (less than 0.50 hrs) the other storm events are not shown. The storms observed during the study appear to follow closely the storm type IA. Rogowski (1981) also concluded that storm type IA is the most prevalent type of storm in Central Pennsylvania. Therefore, storm type parameters (Table 3.1) were used to calculate the rainfall erosivity factor (R in USLE). These values are shown in Table 4.2.

Storm durations reported in Table 4.1 were obtained by using time compression approximation (Reeves and Miller, 1975). The "Time

Table 4.1. Precipitation information for Summer 1981.

Storms	Magnitude (inches)	Duration (hours)
1	1.50	3.60
2	0.35	0.50
3	1.35	4.00
4	0.85	0.40
5	1.20	3.50

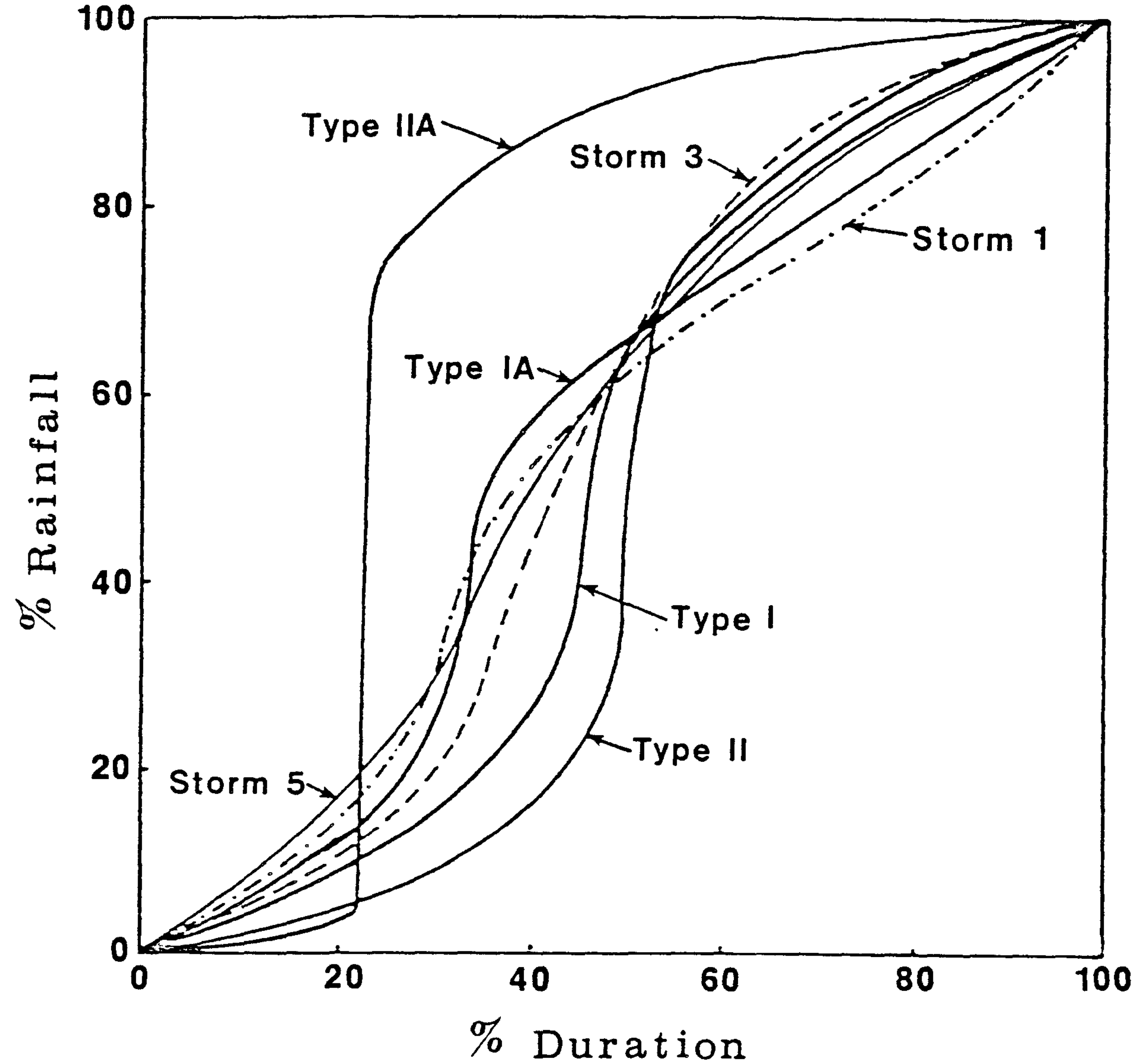


Figure 4.7. Distribution of site storms and SCS storm types.

Table 4.2. Summarized output for storm events of Summer 1981.

Storms	Duration (hrs)	Average Intensity (in/sec.)	Erosivity[a]	Soil Loss[b] (lbs)
1	3.60	0.000116	11.86	228
2	0.50	0.00019	2.39	0
3	4.00	0.000094	8.75	93
4	0.40	0.00059	18.32	53
5	3.50	0.000095	7.51	61

[a](T/A)/(1/100 ft-T/A in/hr).

[b]Predicted soil leaving the area ABDC.

Compression" is a method sometimes used for typical unsteady rainfall events in watershed modeling. In the method the assumption is that for a given soil the maximum infiltration rate depends on the cumulative infiltration and not on the rainfall-time distribution. More specifically, it was indicated (Reeves and Miller, 1975) that for intermittent rainfall events, if the rainfall resumes after a period of drizzle or no rain, the water profile will achieve a shape very similar to that which would have developed after a continuous rainfall event that had the same total infiltration. This method was used here to reduce computationally the effect of interruptions on rainfall intensity, which plays a major role in soil detachment.

4.3.4. Soil Erodibility

The erodibility factor (K) of each portion of the selected site was reported (Rogowski, 1979) and is shown in Figure 4.8. This figure also shows the topsoiled and nontopsoiled areas of the site. Very low values of K on nontopsoiled spoil reflect extensive erosion pavement development and extreme rockiness. Erodibility was assumed to be constant during the study period.

4.3.5. Watershed Cover and Management Factors

The watershed vegetation density is presented in Figure 4.9. This information based on site quadrant survey was used to estimate cover

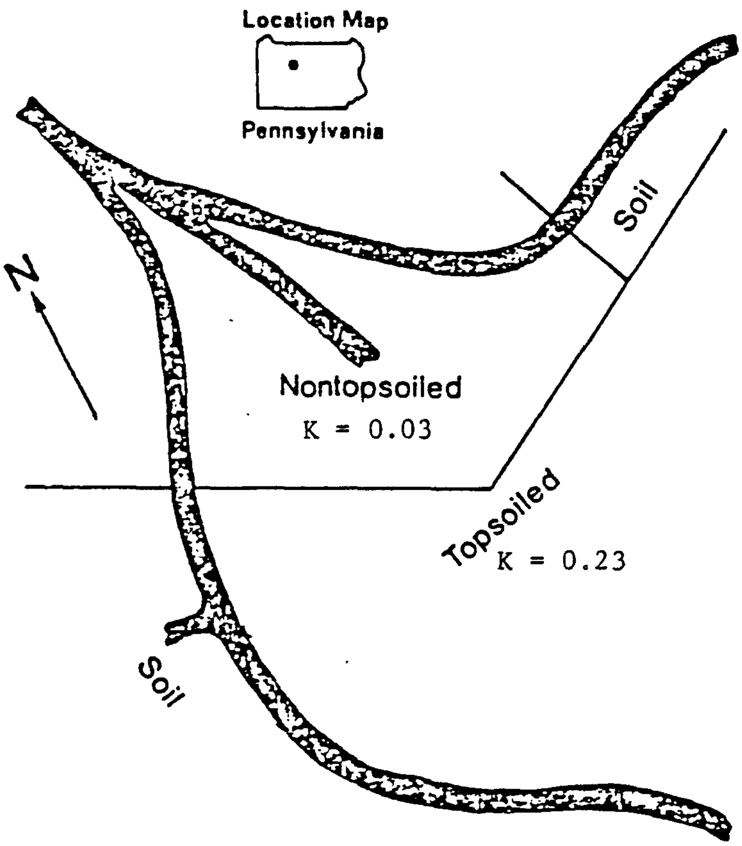


Figure 4.8. Soil erodibility of the selected watershed.

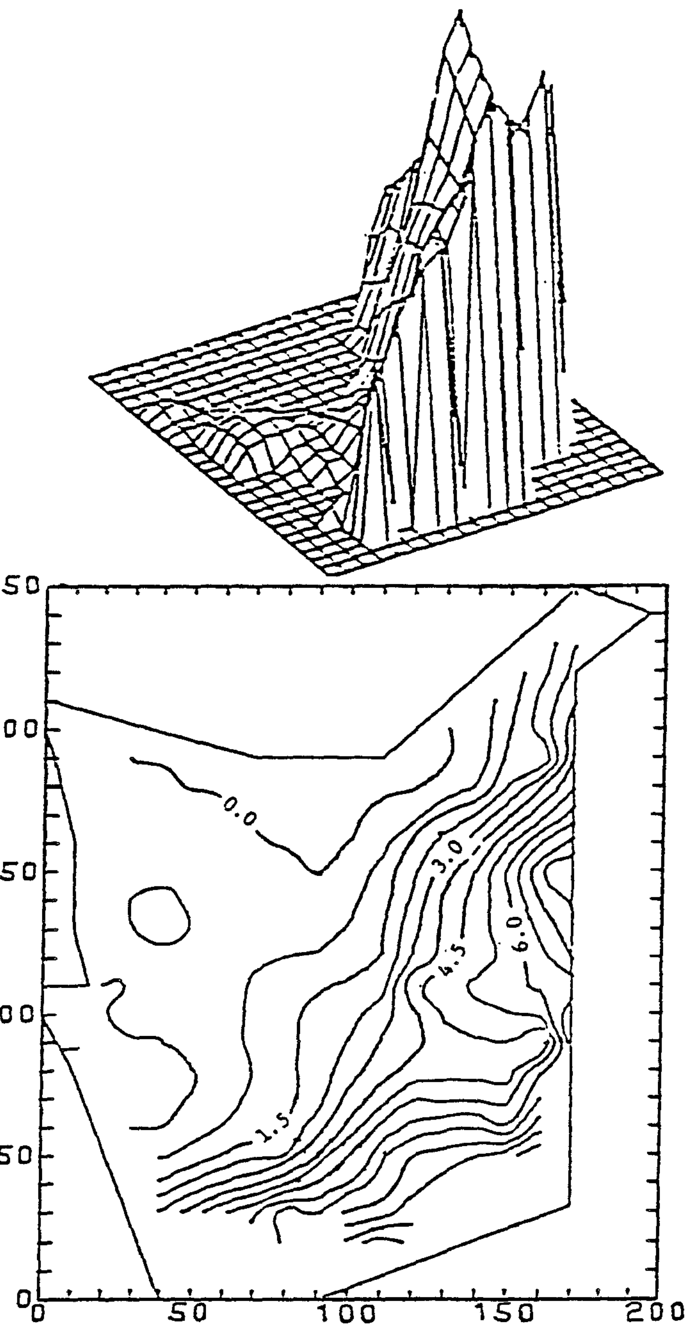


Figure 4.9. Vegetation density (lbs/100 sq ft) of the selected watershed, three and two dimensions.

factor (C) (Wischmeier and Smith, 1978) for the Universal Soil Loss Equation. In this approach, the vegetation density of 0.06 lb/sq ft was taken to be equal to 50% ground cover (Wischmeier and Smith, 1978).

There is no conservation practice management in this watershed. Therefore, the practice management factor (P in Equation 3.5) was set equal to one for the entire area.

4.3.6. Watershed General Parameters

The other parameters used in the application of the model are tabulated in Table 4.3. They were kept constant for all parts of the watershed. Although their numerical values were assumed, they are representative of the watershed conditions.

4.4. Subwatersheds Grouping

As it was discussed earlier, a portion (460 ft x 320 ft) of the site was selected for model application. This portion (area ABDC in Figure 4.3) was divided into 1472 square subwatersheds (subareas). Figure 4.10 shows this grouping and also indicates the numbering of the subwatersheds from upslope to downslope (in this case from south to north). As it is indicated, there are 32 rows with 46 subwatersheds in each row. Each subwatershed is 10 by 10 sq ft.

Table 4.3. Assigned input information for the entire watershed.

Parameter	Magnitude	Unit
Overland flow density	62.5	lb/ft^3
Soil particle density	165.5	lb/ft^3
Temperature	60	F
Overland flow viscosity	0.000012	ft^2/sec
Gravity acceleration	32.2	ft/sec^2

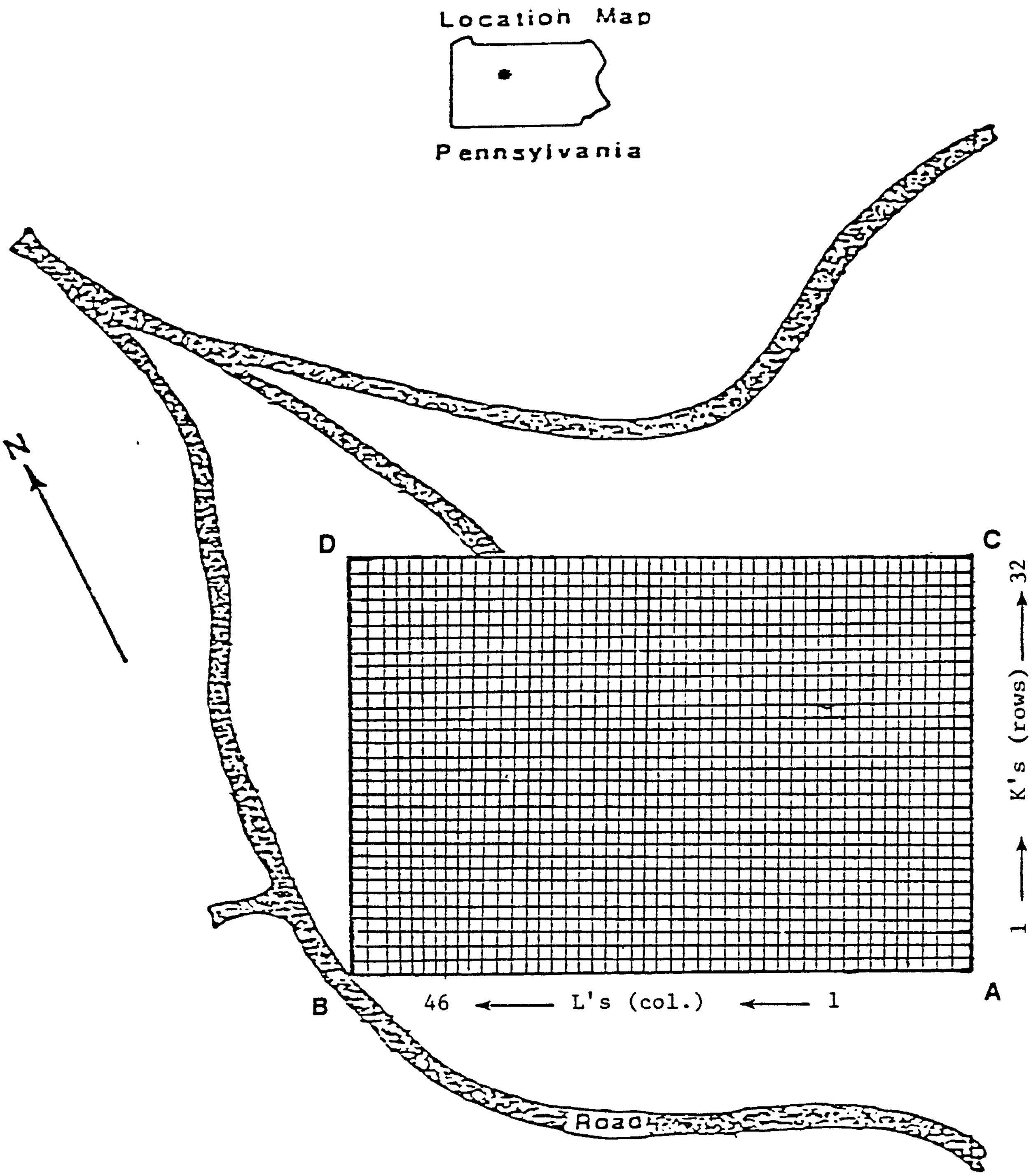


Figure 4.10. Watershed ABCD and its grid system.

4.5. Results and Discussion

The model was run for each storm event reported in Table 4.1. After determining the infiltration at each subwatershed, the available runoff for the start of a rill was checked. The rill patterns and contributing interrill areas were then generated. Figure 4.11 shows the rill patterns and the contributing interrill areas generated by the model using the input data for storm 1. Figure 4.12 shows the eroded soil available for transport at each rill node after the storm 1 has ended, while Figure 4.13 indicates the net amount of soil removed (negative) or deposited (positive), by rill flow after the runoff has ended for a section of area ABDC. The runoff period was assumed to equal the storm period. The deposition values in Figure 4.12 may be thought of as the total amount of sediment recovered at the indicated points and includes the components of both sheet erosion from contributing areas and rill scour. Figure 4.12 indicates that although a great amount of soil was removed from different locations of the area ABDC, only 22 pounds of soil actually left the area. The rest of the detached soil was deposited before reaching the outlet boundary. The total amount of soil leaving the area ABDC for storm 1 was determined to be 228 pounds. Using the same procedure, the same type of results were obtained (not shown) for other four storm events in Table 4.1.

Table 4.2 indicates the net amount of soil leaving the area ABDC for each storm. Also presented in this table are the rainfall

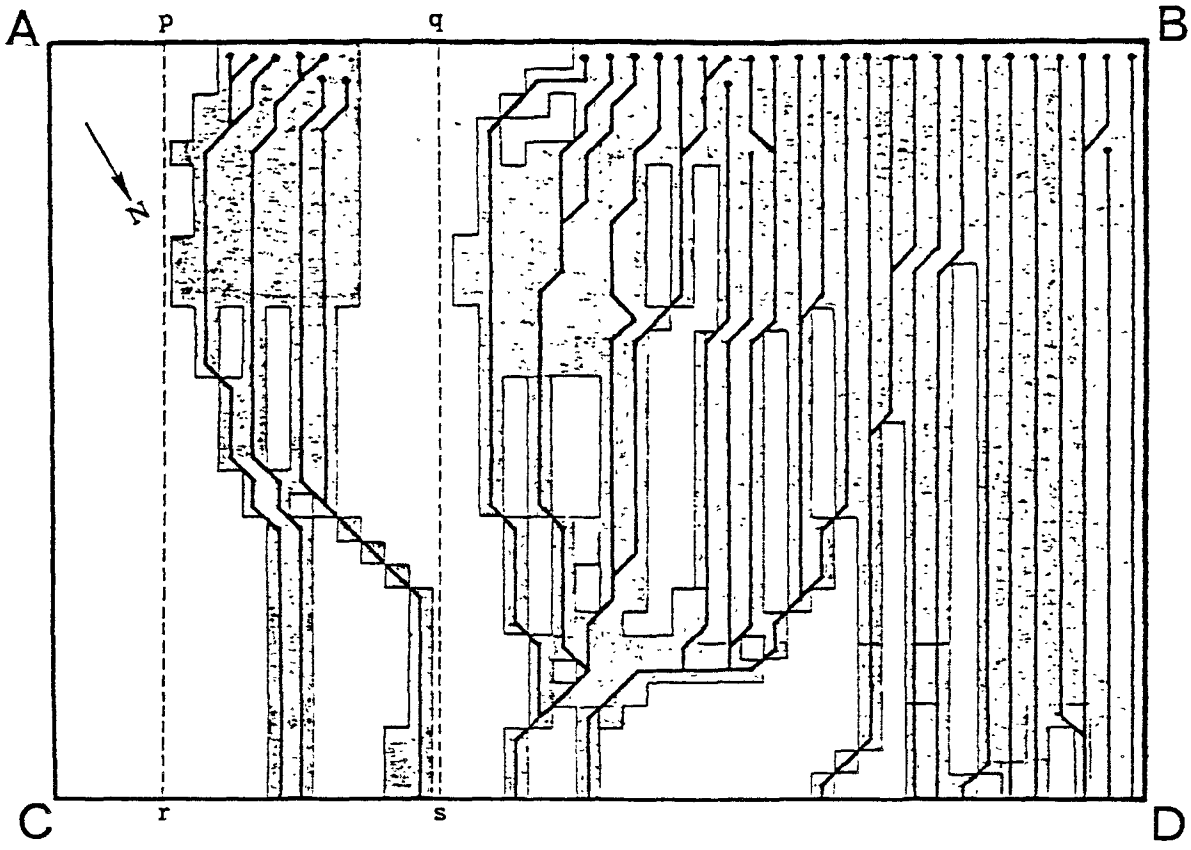


Figure 4.11. Rill patterns and contributing areas (shadow areas) generated by model for storm 1.

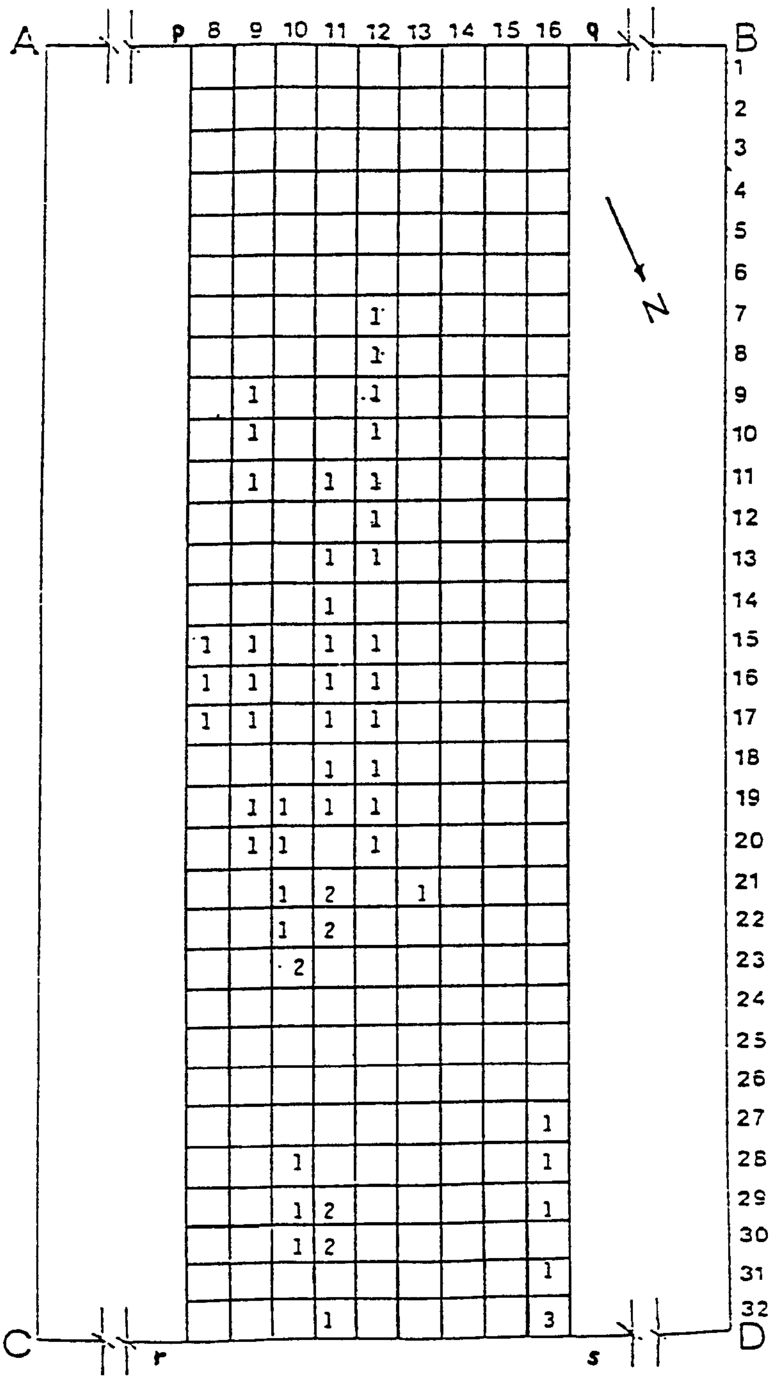


Figure 4.12. Eroded soil (lbs) available for transport at the end of storm 1 for section pqrs of area ABCD.

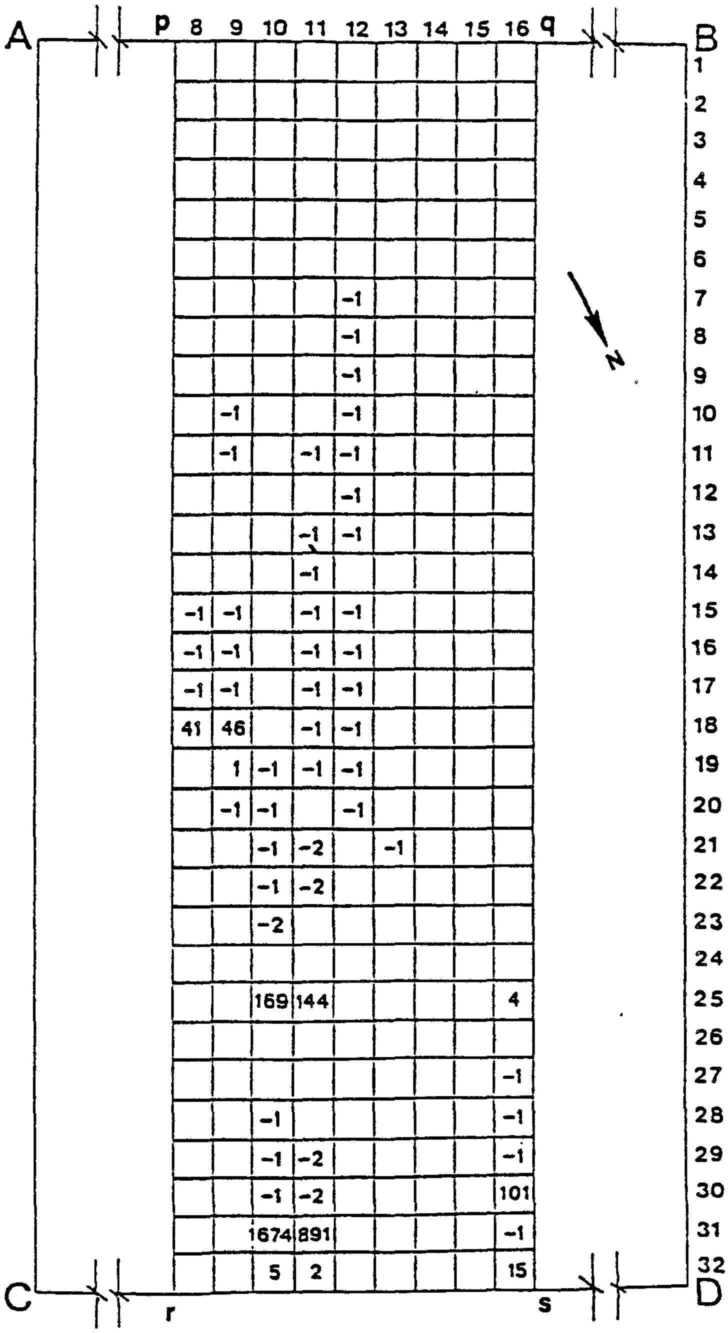


Figure 4.13. Net amount (lbs) of soil eroded (-) or deposited (+) at the end of runoff period after storm 1 for section pqrs of area ABDC.

erosivity factor (R in USLE) which were determined using the model. This table illustrates the roles of rainfall intensity, duration, and erosivity on the magnitude of soil loss. Storm 4 was the most erosive among all the storm events. But, due to its short duration, it did not produce a great amount of soil loss compared to storm 1. According to these results, storm 1 and 2 were the most and least effective rainfall events with regards to the total soil loss from the area ABDC, respectively. Even though their average intensities were similar in magnitude both the duration and soil loss differed considerably. The final result was obtained by summing up the total erosion and deposition for each event. Figure 4.14 shows the composite areas of erosion and deposition at the end of study period.

The erosion and deposition distribution on the watershed is one of the benefits obtained from this model. Figure 4.14 illustrates the utility of the model for locating areas that are susceptible to sediment erosion or deposition on the area ABDC. This type of information may be useful for evaluating the impact of non-point sources of pollution in an area. Figure 4.14 could also be presented as an iso-erosion and deposition map (contours of equal erosion and deposition). However, because of the large range in magnitude of erosion and deposition the results were not presented as an iso-erosion and deposition map.

To check the model result, actual data of erosion and deposition from the watershed for the study period were needed. Erosion and deposition was measured experimentally on the study area. These

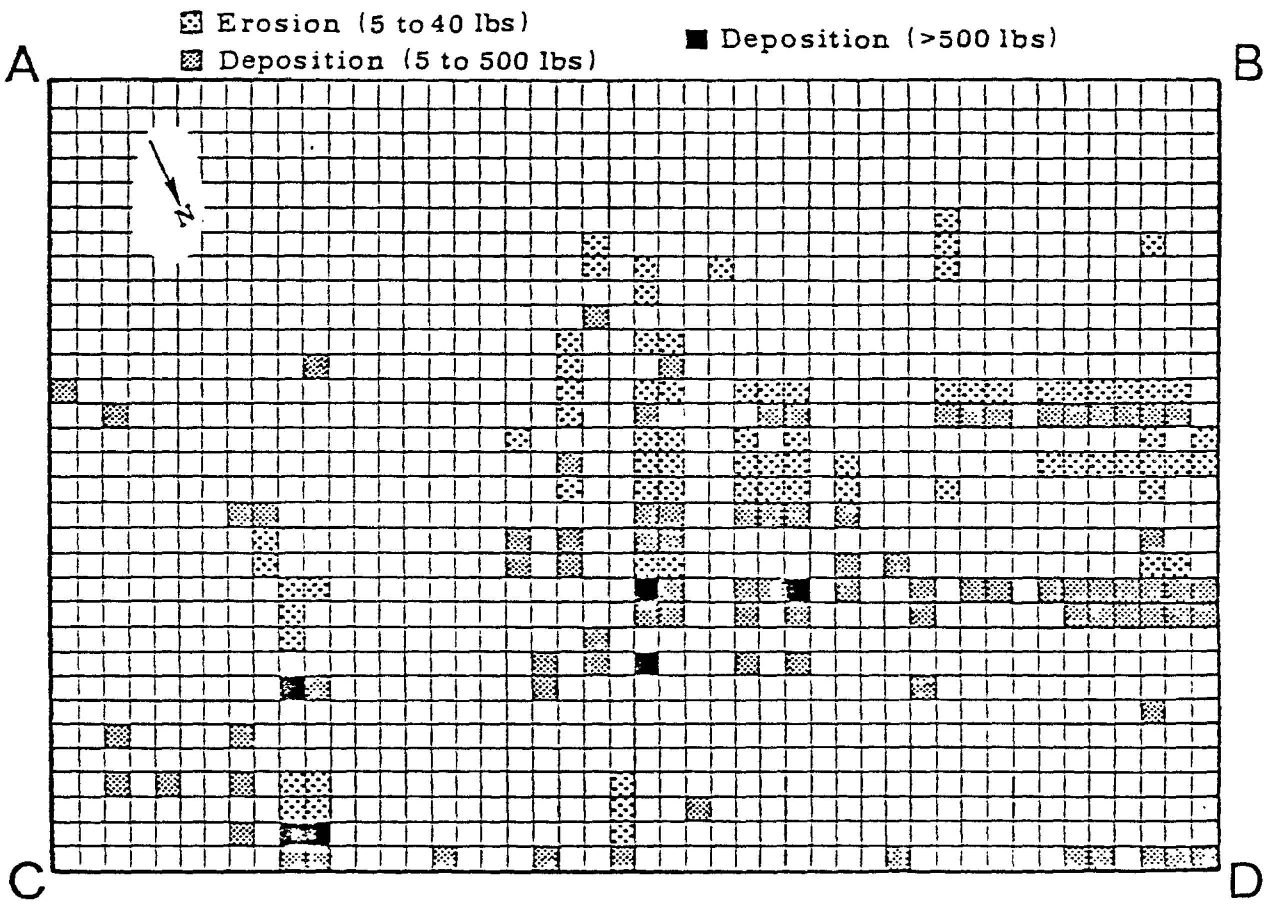


Figure 4.14. Areal distribution of erosion and deposition on each subwatershed.

measurements were accomplished by using metal rods (pins) distributed over the area ABDC. These erosion pins were driven into the soil and changes in their elevation were measured with a special micrometer system accurate to 0.01 inches. Figure 4.15 presents the details of the pin and its measuring technique. The distribution of the pins over the area ABDC is shown in Figure 4.16.

To illustrate the model accuracy, sections MM' and GG' of Figure 4.16 were chosen for a more detailed study. Figures 4.17 and 4.18 show the changes in land elevation during Summer 1981. These results indicated that model prediction tended to follow the experimental variations at the measured sites. In the transects MM' and GG' erosion predicted by the model is less than the values obtained from the measuring pins, however, deposition predicted by the model is more than that measured using the pins. The underprediction of erosion by the model could be related to the fact that most of the parameters used in the model application were assumed to be constant for the entire study period, and throughout the study area. The over-prediction of deposition may be due to changes in rill transport capacity not necessarily accounted for by the specific position of erosion pins. There is also some evidence that erosion pins tend to overpredict actual erosion and underpredict deposition (Sams, 1982).

To evaluate the model performance, a comparison between the predicted and recorded sediment load for the watershed was necessary. Since the measured and predicted values coincided only at thirteen points within the study area, a kriging procedure (Sampson, 1978) was

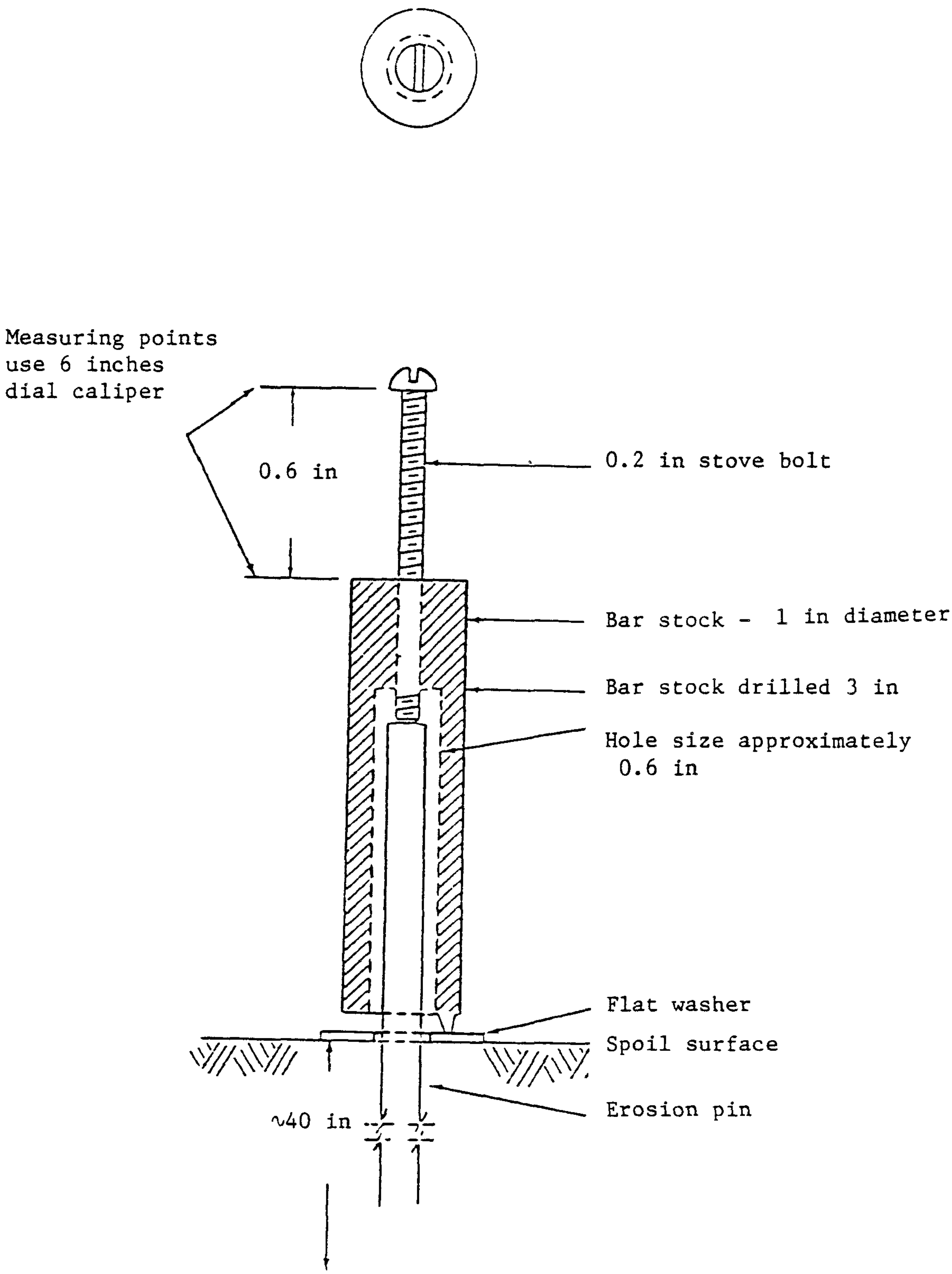


Figure 4.15. Details of erosion pin.

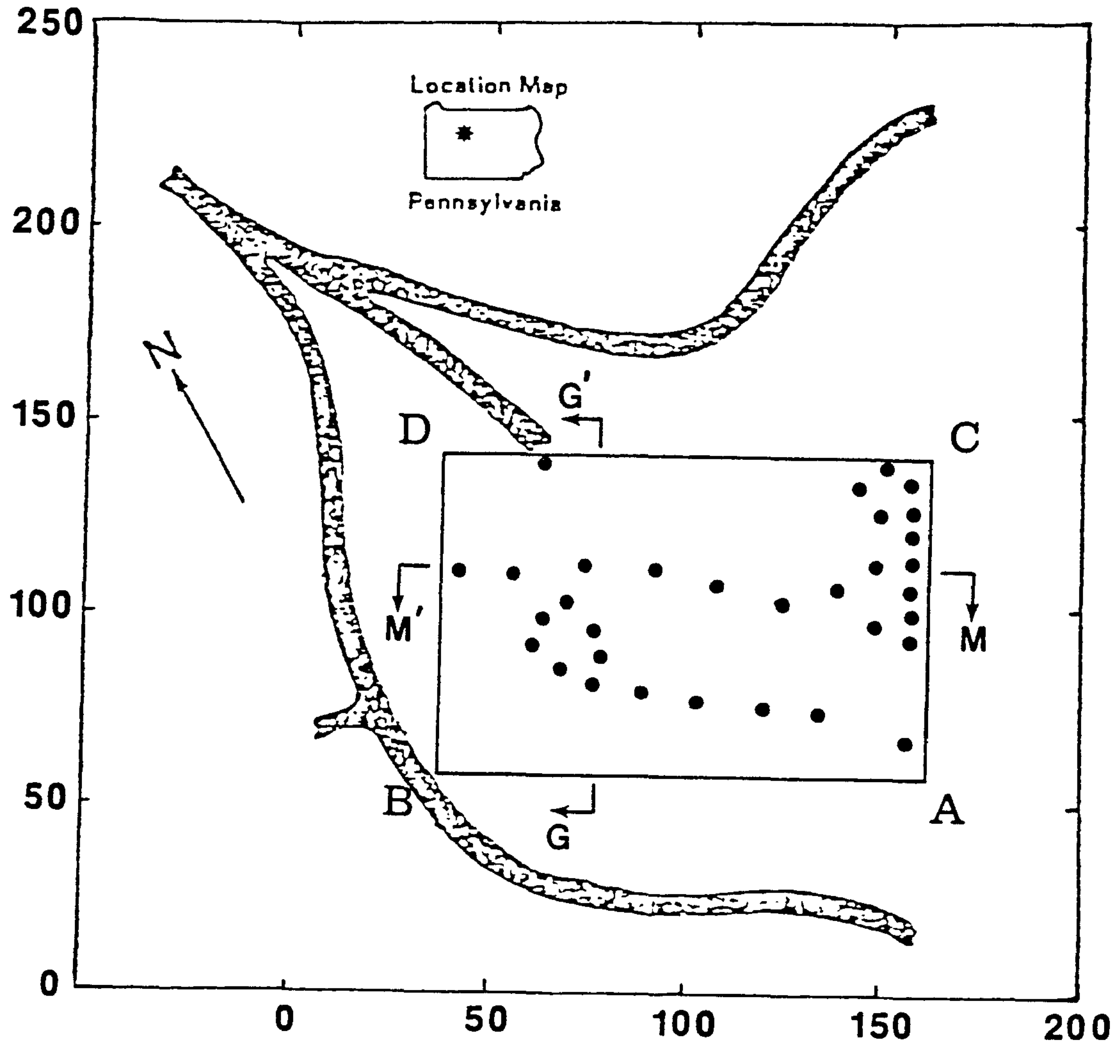


Figure 4.16. Erosion pins (•) distribution over the watershed ABDC.

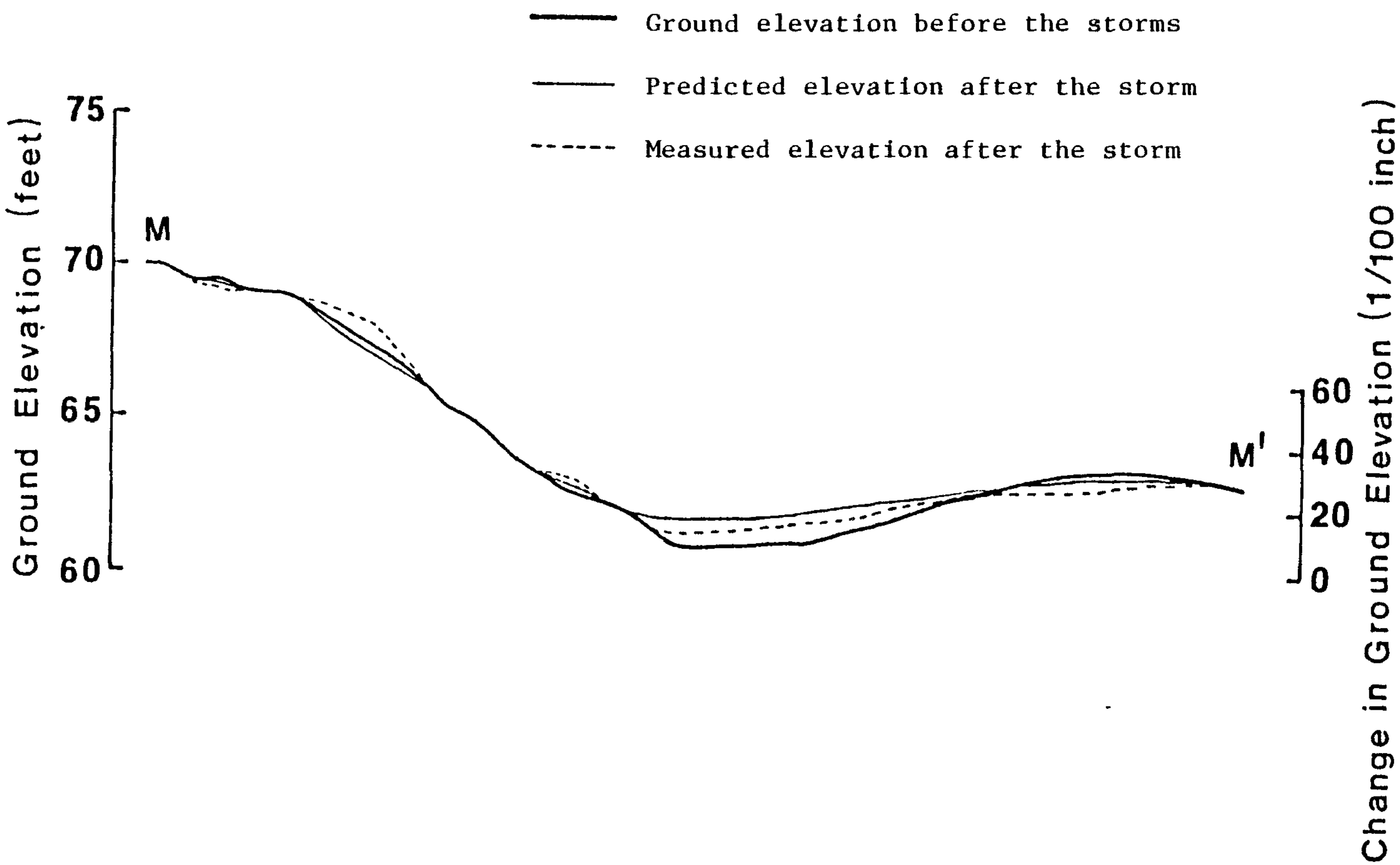


Figure 4.17. Erosion and deposition details of section MM'.

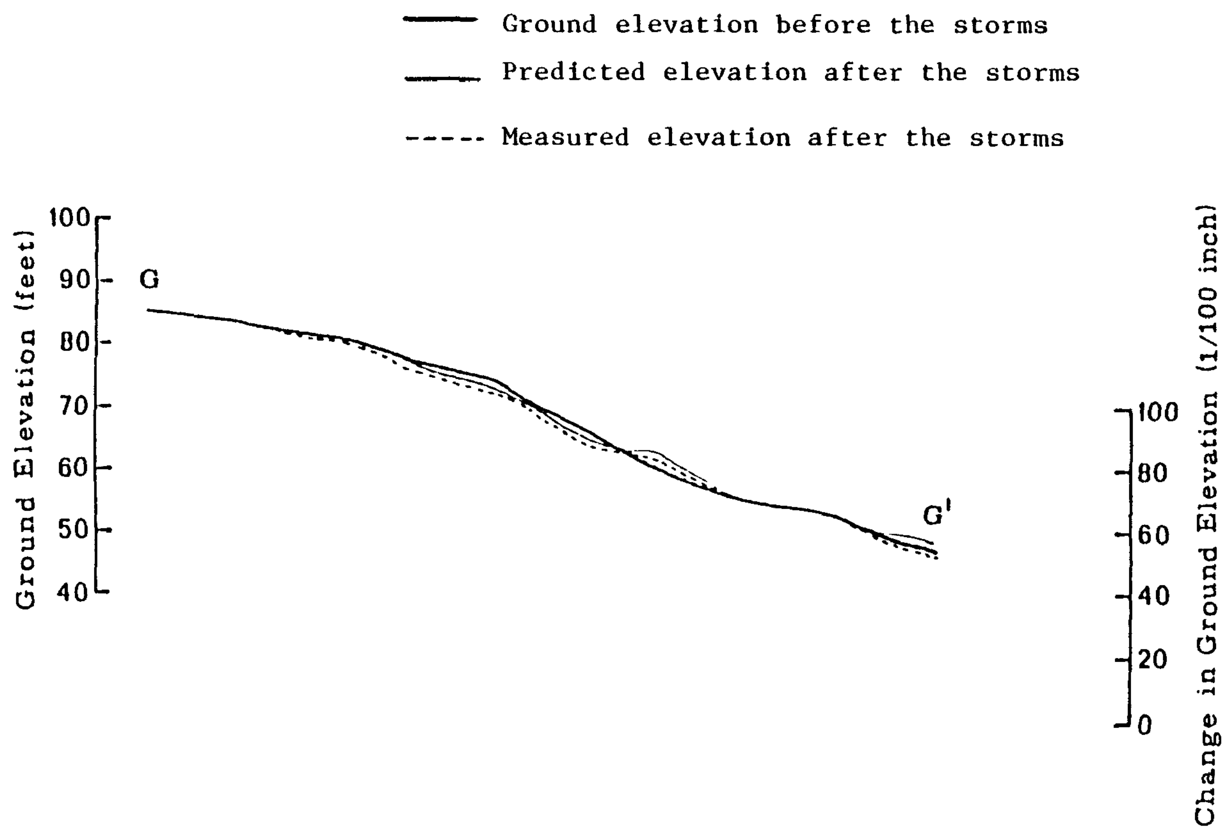


Figure 4.18. Erosion and deposition details of section GG'.

used to get best estimates of measured values at other points where no recorded data was available and, according to the model, significant erosion or deposition was occurring. The resulting correlation (r = 0.88) and regression lines between predicted and measured values of the erosion and deposition (cumulative for all five storms) over area ABDC are shown in Figure 4.19. In this figure the predicted values are about 1.25 times the measured values. Thus, for the study area the model was within plus or minus 25% of the measured erosion and deposition.

The model actually goes one step further and predicts the sediment load at the stream or watershed outlet. However, because there was no data available at the watershed outlet it was not possible to check these values.

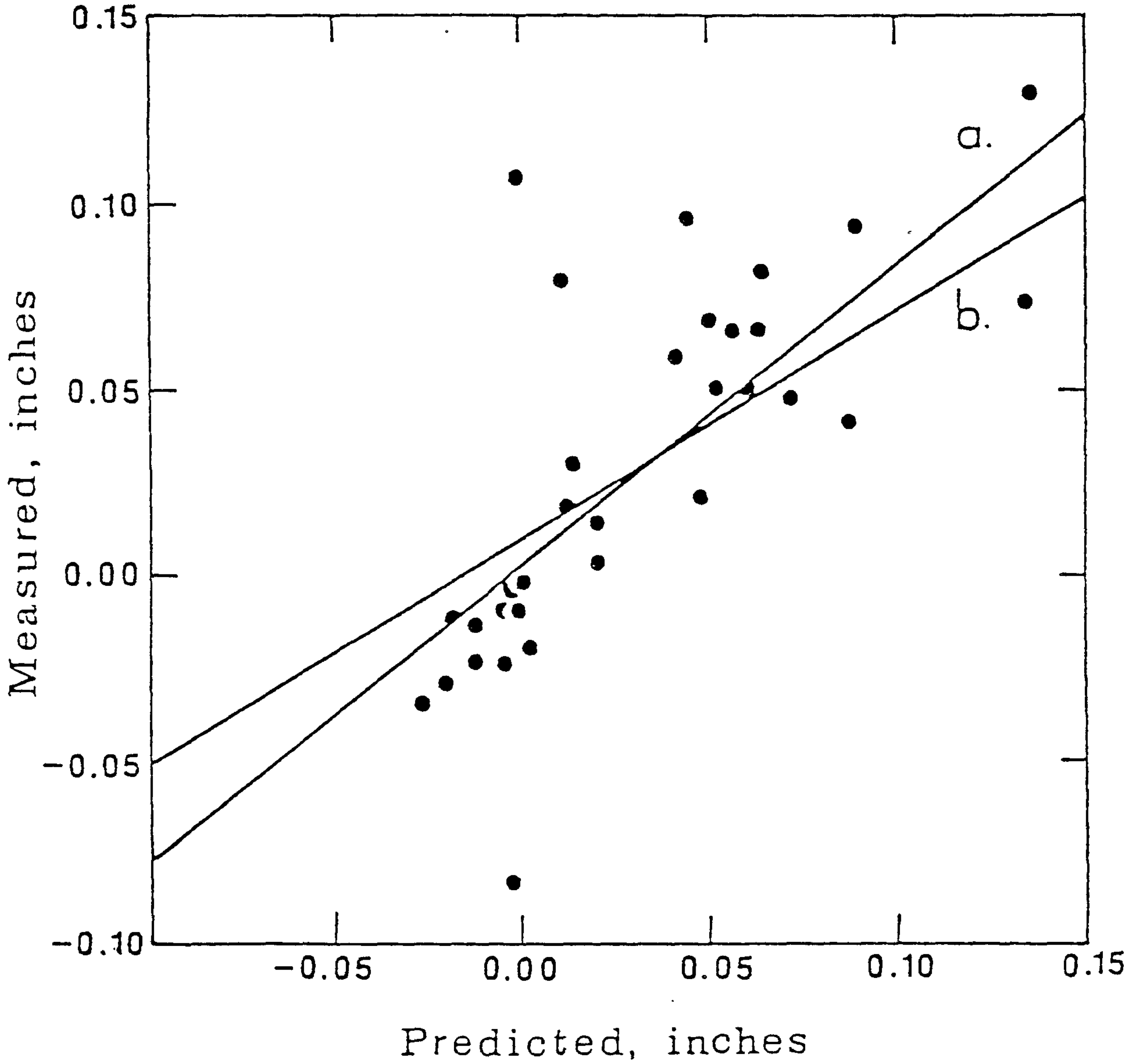


Figure 4.19. Comparison of the predicted and measured erosion and deposition for watershed ABDC. (Note: Curve a is for measured/predicted values and curve b is for predicted/measured values)

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APPENDIX A

EROSION SEDIMENT YIELD MODEL "KEM"

Note: KEM would be available from the Civil Engineering Department at The Pennsylvania State University and from USDA-ARS, University Park.

```
C                             *************************************
C                             *THIS PROGRAM  DETERMINES  THE  RILLS*
C                             * PATTERN,CONTRIBUTING ZONES,EROSION *
C                             * AND DEPOSITION OVER THE WATERSHED  *
C                             *************************************
C
C
C
C        INPUT PARAMETERS AND THEIR DEFINITION
C  *************************************************************
C
C
C      E=ELEVATION OF EACH POINT  (OF THE GRID SYSTEM) IN FT.
C      S = SORPTIVITY (IN/SQ ROOT OF SEC.)
C      A =  A - VALUE FACTOR (INCH/SEC.) TO BE USED IN PHILIP'S(1957) EQ.
C      L1=THE DISTANCE BETWEEN THE GRID POINTS(IN FT.)
C      RR=AVERAGE RAINFALL INTENSITY (IN./SEC.)
C      KK=NUMBER OF GRID POINTS IN VERTICAL DIRECTION (NO. OF ROWS)
C      LL=NUMBER OF GRID POINTS IN HORIZONTAL DIRECTION(NO. OF COL.)
C      T1=DESIRED TIME AFTER THE START OF RAINFALL'(SEC.)
C      T=TOTAL DURATION OF RAINFALL(HOURS)
C      P=TOTAL AMOUNT OF RAINFALL (INCHES)
C      D & B = COEFFICIENTS DEPENDING ON THE TYPE OF STORM(SCS TYPES)
C              (SCS STORM TYPES ARE: I, IA, II, IIA)
C      C= CROP - COVER   FACTOR IN UNIVERSAL SOIL LOSS EQUATION(USLE)
C      PP=PRACTICE MANAGEMENT FACTOR IN USLE
C      KE=SOIL ERODIBILITY FACTOR TO BE USED IN USLE(TONS/ACRE/EI)
C      TIM=THE TIME AFTER THE START OF RUNOFF WHICH EROSION IS WANTED
C      US=SPECIFIC WEIGHT OF SOIL
C      VIS=VISCOSITY OF RUNOFF(WATER)
C      SG=SPECIFIC GRAVITY OF SOIL
C
```

```
C
C          OUTPUT PARAMETERS AND THEIR DEFINITION
C   *****************************************************************
C
C
C        MMM=THE MATRIX SHOWING RILL SOURCE,RILL PATTERN,CONTRIBUTING AREA
C        USLE=THE ERODED  SOIL AVAILABLE ALONG THE RILL BEFORE ROUTING(LBS)
C        RUNO=THE RUNOFF AVAILABLE ALONG THE RILL BEFORE ROUTING(CUBIC IN.)
C        CFAA=THE C-COEFFICIENT FOR FED. AVIATION AGENCY´S EQUATION
C        NET=THE ERODED SOIL ALONG THE RILL AFTER ROUTING (LBS)
C        FNET=THE FINAL SCOUR AND DEPOSITION (LBS)
C
C
C
C
C          DIMENSION
C   ******************************************************************
C
C
C
C
      DIMENSION E(100,100),S(100,100),A(100,100),MMM(100,100)
      DIMENSION CFAA(100,100),FINAL(100,100),RAIN(100,100)
      DIMENSION EBP(100,100),NET(100,100),OF(100,100),RUNO(100,100)
      DIMENSION ASS(100,100),RKCP(100,100),USLE(100,100),KE(100,100)
      DIMENSION BUDGET(100,100),FNET(100,100),C(100,100),PP(100,100)
      REAL L1,L2,R,RR,A1,A2,A3,A4,A5,T1,T,KE,LS,LBAR,MIN,NM,LE,NET
      REAL I,I1,I2,I3,I4
```

```
C
C
C          READ THE INPUT DATA
C
C
C
      READ,L1,T1,RR,KK,LL,P,T,D,B,TIM,US,VIS,SG
      DO 1 K=1,KK
1     READ,(E(K,J),J=1,LL)
      DO 2 K=1,KK
2     READ,(S(K,L),L=1,LL)
      DO 3 M=1,KK
3     READ,(A(M,N),N=1,LL)
      DO 44 K=1,KK
44    READ,(C(K,L),L=1,LL)
      DO 55 K=1,KK
55    READ,(KE(K,L),L=1,LL)
      DO 65 K=1,KK
65    READ,(PP(K,L),L=1,LL)
C
C     PRINT THE INPUT INFORMATION
C
      PRINT 6000
      PRINT,'THE INPUT INFORMATION CAN  BE SUMMARIZED AS'
      PRINT,'THE RAINFALL DURATION (HOURS) =',T
      PRINT,'THE RAINFALL AMOUNT (INCHES)  =',P
      PRINT,'THE DISTANCE BETWEEN NODES (FT)=',L1
      PRINT,'THE SOIL PARTICLE DENSITY      =',US
```

```
C
C
C        DETERMINE THE TOTAL PRECIPITATION(R)
C
C
      IF(T1 .LT. T) GO TO 45
      IF(P .EQ. 0.) GO TO 45
      R=P
      GO TO 46
45    R=RR*T1
46    MM=KK/2
      NN=LL/2
C
C        FIND THE DISTANCE(L2) BETWEEN TWO ADJACENT GRID POINTS
C        AT 45 DEGREE ANGLE
C
      L2=ABS(L1*2**0.5)
      PRINT 6000
      PRINT,'                    ***********************************'
      PRINT,'                    *THIS PART OF OUTPUT SHOWS THE RILL*'
      PRINT,'                    * SOURCES  AND  THEIR  PATTERNS    *'
      PRINT,'                    ***********************************'
C
C       SET ALL THE ELEMENTS IN MATRIX "MMM" EQUAL TO ZERO
C        THIS MATRIX WILL SHOW THE RILL SOURCES AND THEIR PATHS
C
      DO 33 K=1,KK
      DO 33 L=1,LL
33    MMM(K,L)=0.
C
C       SET THE PROCEDURE FOR CHECKING ALL THE POINTS
C
      J1=0
114   IF(J1.EQ.KK) GO TO 112
      J1=J1+1
      J=0
111   J=J+1
```

```
      DO 4 K=J1,KK
      DO 4 L=J,LL
C
C      CHECK IF THE POINT HAS NOT ALREADY BEEN IN ANY RILL
C
      IF(MMM(K,L) .EQ. 1) GO TO 4
C
C
C      FIND THE INFILTRATED WATER AT ALL POINTS
C
C
      I=S(K,L)*T1**0.50+A(K,L)*T1
C
C      CORRECT THE ACTUAL INFILTRATION-USE  TRICKER´S EQUATION(1978)
C        USE SUBROUTINE "TRICK" FOR THIS PURPOSE
C
      CALL TRICK(I,T1,I)
      R2=R-I
C
C      CONVERT INCHES TO FEET
C
      R2=R2/12.
      I=I/12.
C
C      FIND THE POINTS WITH EXCESS RAINFALL
C
      IF(R2 .LT. 0.) GO TO 998
C
C
C      CALCULATE THE AVERAGE SLOPE FOR THOSE POINTS WITH RUNOFF
C      SUBROUTINE SLOPES WOULD BE USED FOR THIS PURPOSE
C
C
      CALL SLOPES(K,L,KK,LL,E,L1,L2,B1,B2,B3,B4,B5,AS)
```

```
C
C       FIND THE POINTS THAT FLOW STARTS TO CONCENTRATE(RILL SOURCE)
C
C
        IF(L1 .LE. 30) GO TO 999
C
C
C         FIND RUNOFF-INFILTRATION RATIO
C
C
        RIR=R2/I
        IF(RIR .GT. 1) GO TO 5
        IF(KE(K,L) .GT. 0.50) GO TO 6
        RIR1=1.25-(2.5*KE(K,L))
        IF(RIR1 .GT. RIR) GO TO 5
        GO TO 998
C
C          FIND AND CHECK THE REYNOLD'S NUMBER(REY)
C
999     REY=32.2*AS*R2**3./(3*VIS**2.)
        IF(REY .GT. 500.) GO TO 5
998     IF(L.EQ.LL) GO TO 114
        GO TO 4
C
C       CHECK IF THE SOIL IS ERODIBLE ENOUGH
C
5       IF(KE(K,L) .GT. 0.10) GO TO 6
        GO TO 998
C
C       CHECK IF THERE IS A POSITIVE SLOPE
C
6       IF(AS .GE. 0.)GO TO 7
        GO TO 998
4       CONTINUE
        GO TO 112
```

```
C
C
C        PRINT THE RILL SOURCE
C
C
7       PRINT,' '
        PRINT,'    THE START  OF RILL IS AT  K=',K,'  AND   L=',L
        PRINT,'               '
C
C        SPECIFY THE RILL SOURCES WITH 10 IN MATRIX "MMM"
C
        MMM(K,L)=10.
        J1=K
        J=L
        PRINT,' THE RILL WOULD PASS THROUGH THE FOLLOWING POINTS'
100     CONTINUE
C
C        CALCULATE THE SLOPES OF ALL THE DIRECTION THAT RILL COULD GO
C          "SUBROUTINE SLOPES WOULD BE USED"
C
        CALL SLOPES(K,L,KK,LL,E,L1,L2,A1,A2,A3,A4,A5,AV)
C
C
C         FIND THE AVERAGE SLOPES (ASS) FOR EACH POINT
C
C
        ASS(K,L)=AV
C
C         FIND THE LARGEST SLOPE (RILL WOULD MOVE IN THAT DIRECTION)
C          "SUBROUTINE BIG WOULD FIND THE LARGEST SLOPE
C
        CALL BIG(A1,A2,A3,A4,A5,K,L,KK,LL,III)
        IF(III .EQ. 1) GO TO 101
        IF(III .EQ. 2) GO TO 102
        IF(III .EQ. 3) GO TO 103
        IF(III .EQ. 4) GO TO 104
        IF(III .EQ. 5) GO TO 105
```

```
C
C        PRINT THE PATTERN OF RILL MOVEMENT
C
101      L=L+1
         PRINT,'K=',K,'L=',L
         GO TO 110
102      K=K+1
         L=L+1
         PRINT,'K=',K,'L=',L
         GO TO 110
103      K=K+1
         PRINT,'K=',K,'L=',L
         GO TO 110
104      K=K+1
         L=L-1
         PRINT,'K=',K,'L=',L
         GO TO 110
105      L=L-1
         PRINT,'K=',K,'L=',L
         GO TO 110
C
C        SPECIFY THE RILL PATHS WITH 1 IN MATRIX "MMM"
C
110      MMM(K,L)=1.
         IF(K .EQ. KK) ASS(K,L)=ABS((E(K,L)-E(K-1,L))/L1)
         IF(K .EQ. KK) GO TO 113
         GO TO 100
113      IF(J.EQ.LL) GO TO 114
         GO TO 111
112      CONTINUE
C
C
C
C         FIND THE EROSION CONTRIBUTING AREAS TO THE RILLS (PARTIAL AREAS)
C
```

```
C
      DO 200 K=1,KK
      DO 200 L=1,LL
C
C      CHECK ALL THE INTERRILL POINTS ADJACENT TO RILLS
C
      IF(MMM(K,L) .EQ. 10) GO TO 201
      IF(MMM(K,L) .EQ. 1) GO TO 201
      GO TO 200
201   IF(K .EQ. 1) GO TO 202
      GO TO 206
202   IF(L .EQ. 1) GO TO 203
      IF(L .EQ. LL) GO TO 204
      GO TO 205
206   IF(K .EQ.KK)GO TO 207
      GO TO 208
207   IF(L .EQ.1)GO TO 209
      IF(L .EQ. LL)GO TO 231
      GO TO 232
208   IF(L .EQ. 1) GO TO 233
      IF(L .EQ. LL) GO TO 223
      GO TO 234
C
C      DETERMINE THE INFILTRATION ON INTERRILL AREAS
C
203   I1=S(K,L+1)*T1**0.50+A(K,L+1)*T1
C
C       MAKE THE CORRECTION FOR ACTUALL INFILTRATION
C        USE SUBROUTINE "TRICK"
C
      CALL TRICK(I1,T1,I1)
      IF(MMM(K,L+1).EQ. 10) GO TO 230
      IF(MMM(K,L+1).EQ. 1) GO TO 230
```

```
C
C       CHECK IF THERE IS A RAINFALL EXCESS
C       SET THESE CONTRIBUTING AREAS AS 8 IN MATRIX "MMM"
C
        IF(R .GT. I1) MMM(K,L+1)=8.
230     I2=S(K+1,L)*T1**0.50+A(K+1,L)*T1
        CALL TRICK(I2,T1,I2)
        IF(MMM(K+1,L).EQ. 10) GO TO 200
        IF(MMM(K+1,L).EQ. 1) GO TO 200
        IF(R .GT. I2) MMM(K+1,L)=8.
        GO TO 200
204     I3=S(K,L-1)*T1**0.50+A(K,L-1)*T1
        CALL TRICK(I3,T1,I3)
        IF(MMM(K,L-1).EQ. 10) GO TO 230
        IF(MMM(K,L-1).EQ. 1) GO TO 230
        IF(R .GT. I3) MMM(K,L-1)=8.
        GO TO 230
205     I3=S(K,L-1)*T1**0.50+A(K,L-1)*T1
        CALL TRICK(I3,T1,I3)
        IF(MMM(K,L-1).EQ. 10) GO TO 203
        IF(MMM(K,L-1).EQ. 1) GO TO 203
        IF(R .GT.I3) MMM(K,L-1)=8.
        GO TO 203
209     I4=S(K-1,L)*T1**0.50+A(K-1,L)*T1
        CALL  TRICK(I4,T1,I4)
        IF(MMM(K-1,L).EQ. 10) GO TO 210
        IF(MMM(K-1,L).EQ. 1) GO TO 210
        IF(R .GT. I4) MMM(K-1,L)=8.
        A1=A(K,L+1)
210     I1=S(K,L+1)*T1*0.50+A(K,L+1)*T1
        CALL TRICK(I1,T1,I1)
        IF(MMM(K,L+1).EQ. 10) GO TO 200
        IF(MMM(K,L+1).EQ. 1) GO TO 200
        IF(R .GT. I1) MMM(K,L+1)=8.
        GO TO 200
```

```
231     I3=S(K,L-1)*T1**0.50+A(K,L-1)*T1
        CALL TRICK(I3,T1,I3)
        IF(MMM(K,L-1).EQ. 10) GO TO 211
        IF(MMM(K,L-1).EQ. 1) GO TO 211
        IF(R .GT. I3) MMM(K,L-1)=8.
211     I4=S(K-1,L)*T1**0.50+A(K-1,L)*T1
        CALL TRICK(I4,T1,I4)
        IF(MMM(K-1,L).EQ. 10) GO TO 200
        IF(MMM(K-1,L).EQ. 1) GO TO 200
        IF(R .GT.I4) MMM(K-1,L)=8.
        GO TO 200
232     I1=S(K,L+1)*T1**0.50+A(K,L+1)*T1
        CALL TRICK(I1,T1,I1)
        IF(MMM(K,L+1).EQ. 10) GO TO 231
        IF(MMM(K,L+1).EQ. 1) GO TO 231
        IF(R .GT. I1) MMM(K,L+1)=8.
        GO  TO 231
233     I2=S(K+1,L)*T1**0.50+A(K+1,L)*T1
        CALL TRICK(I2,T1,I2)
        IF(MMM(K+1,L).EQ. 10) GO TO 209
        IF(MMM(K+1,L).EQ. 1) GO TO 209
        IF(R .GT. I2) MMM(K+1,L)=8.
        GO TO 209
223     I2=S(K+1,L)*T1**0.50+A(K+1,L)*T1
        CALL TRICK(I2,T1,I2)
        IF(MMM(K+1,L).EQ. 10) GO TO 231
        IF(MMM(K+1,L).EQ. 1) GO TO 231
        IF(R .GT. I2) MMM(K+1,L)=8.
        GO TO 231
234     I1=S(K,L+1)*T1**0.50+A(K,L+1)*T1
        CALL TRICK(I1,T1,I1)
        IF(MMM(K,L+1).EQ. 10) GO TO 223
        IF(MMM(K,L+1).EQ. 1) GO TO 223
        IF(R .GT. I1) MMM(K,L+1)=8.
```

```
      GO TO 223
200   CONTINUE
C
C
C      PRINT THE RILLS PATTERNS
C
C
      PRINT 6000
6000  FORMAT('1',T40,'*********************************************')
      PRINT 6002
6002  FORMAT(' ',T39,'*   THE FOLLOWING CHART SHOWS THE START OF    *')
      PRINT 6003
6003  FORMAT(' ',T39,'*   RILLS (AS *) AND THE RILLS PATTERNS (AS 1)*')
      PRINT 6006
6006  FORMAT(' ',T39,'*   AND THE EROSION CONTRIBUTING AREAS TO THE *')
      PRINT 6007
6007  FORMAT(' ',T39,'*   RILLS (AS 8).  ZEROS ARE THE OTHER ZONES  *')
      PRINT 6008
6008  FORMAT(' ',T40,'*********************************************')
      PRINT,' '
      PRINT,' '
      DO 222 K=1,KK
      WRITE(6,6001)(MMM(K,L),L=1,LL)
6001  FORMAT(' ',100I1)
222   CONTINUE
C
C
C     CALCULATE THE OVERLAND FLOW AT ALL POINTS OF THE WATERSHED
C
C
      DO 298 K=1,KK
      DO 298 L=1,LL
      I=S(K,L)*T1**0.50+A(K,L)*T1
```

```
C
C          CORRECT THE INFILTRATION
C           USE SUBROUTINE "TRICK"
C
      CALL TRICK(I,T1,I)
      OF(K,L)=R-I
      IF(OF(K,L) .LT. 0.0) OF(K,L)=0.
298   CONTINUE
C
C      DETERMINE THE RAINFALL ALONG THE RILL POINTS
C
      DO 301 K=1,KK
      DO 301 L=1,LL
      IF(MMM(K,L) .EQ. 10)  MMM(K,L)=1.
      IF(MMM(K,L) .EQ. 1) GO TO 299
C
C          SET THE INITIAL MATRICES CONDITION
C
      RKCP(K,L)=0.
      USLE(K,L)=0.
      RUNO(K,L)=0.
      RAIN(K,L)=R
      NET(K,L)=0.
      GO TO 301
299   IF(P .NE. 0.) GO TO 300
      P=RR*T*3600.
300   CONTINUE
C
C      USE COOLEY'S APPROACH FOR FINDING R TO BE USED IN USLE
C          " SUBROUTINE COOL WOULD BE USED TO FIND "R" VALUE IN USLE"
C
      CALL COOL(P,T,D,B,RST)
      SS=ASS(K,L)*100
```

```
C
C
C        USE SUBROUTINE MEY TO FIND "LS" VALUE IN USLE
C
C
      CALL MEY(SS,L1,LS)
      RUNO(K,L)=OF(K,L)
      RAIN(K,L)=R
C
C         FIND THE MATRIX RKCP TO BE USED IN USLE
C
      RKCP(K,L)=RST*C(K,L)*KE(K,L)*PP(K,L)
C
C        FIND THE ERODED SOIL AT EACH POINT(USING THE USLE)
C
      USLE(K,L)=LS*RKCP(K,L)
301   CONTINUE
C
C
C     DETERMINE THE ERODED SOIL AND RUNOFF VALUES CORRESPONDING TO
C     THE PARTIAL AREAS AND DISTRIBUTE THEM ALONG THE RILLS PATTERN
C
C
      DO 390 K=1,KK
      DO 390 L=1,LL
      IF(MMM(K,L) .EQ. 0.) ASS(K,L)=0.
      IF(MMM(K,L) .NE. 8) GO TO 390
      LBAR=ABS(L1**0.50)
C
C        USE "USLE" FOR CALCULATING INTERRILL EROSION
C
      RKCP(K,L)=RST*KE(K,L)*C(K,L)*PP(K,L)
      IF(L .EQ. 1) GO TO 302
      GO TO 310
```

```
302   IF(K .EQ. KK) GO TO 303
      GO TO 305
303   IF(MMM(K,L+1) .EQ. 1) GO TO 385
      IF(MMM(K-1,L+1) .EQ. 1) GO TO 304
      GO TO 382
304   IF(E(K-1,L) .GT. E(K-1,L+1)) GO TO 383
      GO TO 382
305   IF(MMM(K+1,L+1) .EQ. 1) GO TO 306
      GO TO 308
306   IF(MMM(K+1,L) .EQ. 1) GO TO 307
      GO TO 388
307   IF(E(K+1,L) .GT. E(K+1,L+1)) GO TO 388
      GO TO 387
308   IF(MMM(K+1,L) .EQ. 1) GO TO 387
      IF(MMM(K,L+1) .EQ. 1) GO TO 385
      IF(MMM(K-1,L+1) .EQ. 1) GO TO 309
      GO TO 382
309   IF(E(K-1,L+1) .GT. E(K-1,L)) GO TO 382
      GO TO 383
310   IF(L .EQ. LL) GO TO 311
      GO TO 341
311   IF(K .EQ. KK) GO TO 312
      GO TO 314
312   IF(MMM(K,L-1) .EQ. 1) GO TO 384
      IF(MMM(K-1,L-1) .EQ. 1) GO TO 313
      GO TO 382
313   IF(E(K-1,L) .GT. E(K-1,L-1)) GO TO 381
      GO TO 382
314   IF(MMM(K+1,L-1) .EQ. 1) GO TO 315
      GO TO 317
315   IF(MMM(K+1,L) .EQ.1) GO TO 316
      GO TO 386
```

```
C
C        FIND THE POINT THAT INTERRILL ERODED SOIL IS TRANSPORTED TO
C
316     IF(E(K+1,L) .GT. E(K+1,L-1)) GO TO 386
        GO TO 387
317     IF(MMM(K+1,L) .EQ. 1) GO TO 387
        IF(MMM(K,L-1) .EQ. 1) GO TO 384
        IF(MMM(K-1,L-1) .EQ. 1) GO TO 318
        GO TO 382
318     IF(E(K-1,L-1) .GT. E(K-1,L)) GO TO 382
        GO TO 381
341     IF(K .EQ. KK) GO TO 340
        GO TO 319
319     IF(MMM(K+1,L-1) .EQ. 1) GO TO 320
        GO TO 328
320     IF(MMM(K+1,L) .EQ. 1) GO TO 321
        GO TO 326
321     IF(MMM(K+1,L+1) .EQ. 1) GO TO 322
        GO TO 325
322     IF(E(K+1,L-1) .GT. E(K+1,L+1)) GO TO 323
        GO TO 324
323     IF(E(K+1,L+1) .GE. E(K+1,L)) GO TO 387
        GO TO 388
324     IF(E(K+1,L-1) .GE. E(K+1,L)) GO TO 387
        GO TO 386
325     IF(E(K+1,L-1) .GE. E(K+1,L)) GO TO 387
        GO TO 386
326     IF(MMM(K+1,L+1) .EQ. 1) GO TO 327
        GO TO 386
327     IF(E(K+1,L-1)-E(K+1,L+1)) 386,337,388
328     IF(MMM(K+1,L) .EQ. 1) GO TO 329
        GO TO 331
```

```
329    IF(MMM(K+1,L+1) .EQ. 1) GO TO 330
       GO TO 387
330    IF(E(K+1,L+1) .GE. E(K+1,L)) GO TO 387
       GO TO 388
331    IF(MMM(K+1,L+1) .EQ. 1) GO TO 388
340    IF(MMM(K,L-1) .EQ. 1) GO TO 332
       GO TO 334
332    IF(MMM(K,L+1) .EQ. 1)GO TO 333
       GO TO 384
333    IF(E(K,L-1)-E(K,L+1)) 384,338,385
334    IF(MMM(K,L+1) .EQ. 1) GO TO 385
       IF(MMM(K-1,L-1) .EQ. 1) GO TO 335
       GO TO 383
335    IF(MMM(K-1,L+1) .EQ. 1) GO TO 336
       GO TO 381
336    IF(E(K-1,L-1)-E(K-1,L+1)) 381,339,383
337       IF(L .GT. NN) GO TO 386
       GO TO 388
338       IF(L .GT. NN) GO TO 384
       GO TO 385
339       IF(L .GT. NN) GO TO 381
       GO TO 383
381    ASS(K,L)=(E(K,L)-E(K-1,L-1))/L2
       SS=ABS(ASS(K,L)*100)
       LS=LBAR*(0.0076+0.0053*SS+0.00076*SS**2)
C
C        SET THE EROSION AND RUNOFF AT RILL POINTS BEFORE ROUTING
C
       USLE(K-1,L-1)=USLE(K-1,L-1)+LS*RKCP(K,L)
       RUNO(K-1,L-1)=RUNO(K-1,L-1)+OF(K,L)
       RAIN(K-1,L-1)=RAIN(K-1,L-1)+R
       GO TO 390
```

```
382   ASS(K,L)=(E(K,L)-E(K-1,L))/L1
      SS=ABS(ASS(K,L)*100)
      LS=LBAR*(0.0076+0.0053*SS+0.00076*SS**2)
      USLE(K-1,L)=USLE(K-1,L)+LS*RKCP(K,L)
      RUNO(K-1,L)=RUNO(K-1,L)+OF(K,L)
      RAIN(K-1,L)=RAIN(K-1,L)+R
      GO TO 390
383   ASS(K,L)=(E(K,L)-E(K-1,L+1))/L2
      SS=ABS(ASS(K,L)*100)
      LS=LBAR*(0.0076+0.0053*SS+0.00076*SS**2)
      USLE(K-1,L+1)=USLE(K-1,L+1)+LS*RKCP(K,L)
      RUNO(K-1,L+1)=RUNO(K-1,L+1)+OF(K,L)
      RAIN(K-1,L+1)=RAIN(K-1,L+1)+R
      GO TO 390
384   ASS(K,L)=(E(K,L)-E(K,L-1))/L1
      SS=ABS(ASS(K,L)*100)
      LS=LBAR*(0.0076+0.0053*SS+0.00076*SS**2)
      USLE(K,L-1)=USLE(K,L-1)+LS*RKCP(K,L)
      RUNO(K,L-1)=RUNO(K,L-1)+OF(K,L)
      RAIN(K,L-1)=RAIN(K,L-1)+R
      GO TO 390
385   ASS(K,L)=(E(K,L)-E(K,L+1))/L1
      SS=ABS(ASS(K,L)*100)
      LS=LBAR*(0.0076+0.0053*SS+0.00076*SS**2)
      USLE(K,L+1)=USLE(K,L+1)+LS*RKCP(K,L)
      RUNO(K,L+1)=RUNO(K,L+1)+OF(K,L)
      RAIN(K,L+1)=RAIN(K,L+1)+R
      GO TO 390
386   ASS(K,L)=(E(K,L)-E(K+1,L-1))/L2
      SS=ABS(ASS(K,L)*100)
      LS=LBAR*(0.0076+0.0053*SS+0.00076*SS**2)
      USLE(K+1,L-1)=USLE(K+1,L-1)+LS*RKCP(K,L)
      RUNO(K+1,L-1)=RUNO(K+1,L-1)+OF(K,L)
      RAIN(K+1,L-1)=RAIN(K+1,L-1)+R
```

```
      GO TO 390
387   ASS(K,L)=(E(K,L)-E(K+1,L))/L1
      SS=ABS(ASS(K,L)*100)
      LS=LBAR*(0.0076+0.0053*SS+0.00076*SS**2)
      USLE(K+1,L)=USLE(K+1,L)+LS*RKCP(K,L)
      RUNO(K+1,L)=RUNO(K+1,L)+OF(K,L)
      RAIN(K+1,L)=RAIN(K+1,L)+R
      GO TO 390
388   ASS(K,L)=(E(K,L)-E(K+1,L+1))/L2
      SS=ABS(ASS(K,L)*100)
      LS=LBAR*(0.0076+0.0053*SS+0.00076*SS**2)
      USLE(K+1,L+1)=USLE(K+1,L+1)+LS*RKCP(K,L)
      RUNO(K+1,L+1)=RUNO(K+1,L+1)+OF(K,L)
      RAIN(K+1,L+1)=RAIN(K+1,L+1)+R
      GO TO 390
390   CONTINUE
C
C      ADJUST THE UNITS OF VARIABLES
C
      DO 392 K=1,KK
      DO 392 L=1,LL
      USLE(K,L)=((USLE(K,L)*L1**2)/43539.24)*2000
      RUNO(K,L)=(RUNO(K,L)*L1**2)*144.
      RAIN(K,L)=(RAIN(K,L)*L1**2)*144
C
C      FIND THE "C-COEFFICIENT" FROM RARIONAL FORMULA APPROACH
C
      CFAA(K,L)=RUNO(K,L)/RAIN(K,L)
C
C      SET AVAILABLE EROSION BEFORE POINTS(EBP)TO ZERO
C
      EBP(K,L)=0.
392   CONTINUE
```

```
C
C      PRINT THE DETACHED SOIL AT EACH POINT BEFORE ROUTING
C
      PRINT 6000
      PRINT 6009
6009  FORMAT(' ',T40,'*  THE ERODED SOIL AVAILABLE ALONG THE RILLS*')
      PRINT 6010
6010  FORMAT(' ',T40,'*        {{{{THE UNIT IS IN  LBS }}}         *')
      PRINT 6008
      PRINT,' '
      PRINT,' '
      DO 391 K=1,KK
      PRINT,' FOR ROW NO.',K
      WRITE(6,6004)(USLE(K,L),L=1,LL)
6004  FORMAT(' ',10F13.0)
      PRINT,'  '
      PRINT,' '
      PRINT,' '
391   PRINT,'  '
C
C      PRINT THE AVAILABLE RUNOFF AT EACH POINT OF RILL BEFOR ROUTING
C
      PRINT 6000
      PRINT 6011
6011  FORMAT(' ',T40,'*  THE  RUNOFF  AVAILABLE ALONG THE RILLS    *')
      PRINT 6012
6012  FORMAT(' ',T40,'*          THE UNIT IS IN CUBIC INCHES       *')
      PRINT 6008
      PRINT,' '
      PRINT,' '
      PRINT,' '
      DO 393 K=1,KK
      PRINT,' FOR ROW NO.',K
      WRITE(6,6005)(RUNO(K,L),L=1,LL)
6005  FORMAT(' ',10F10.2)
```

```
      PRINT,' '
      PRINT,' '
      PRINT,' '
393   PRINT,'  '
C
C      PRINT THE "C-COEFFICIENT" TO BE USED IN " FAA " EQUATION
C
       PRINT 6000
       PRINT 6013
6013   FORMAT(' ',T40,'*   THE C-COEFFICIENT FOR FED. AV. AGENCY   *')
       PRINT 6008
       DO 394 K=1,KK
       PRINT,'ROW NO.',K
       WRITE(6,6014)(CFAA(K,L),L=1,LL)
6014   FORMAT(' ',10F10.1)
       PRINT,' '
       PRINT,' '
       PRINT,' '
394    CONTINUE
      DO 395 K=1,KK
      DO 395 L=1,LL
      NET(K,L)=USLE(K,L)
395   CONTINUE
C
C
C      START THE SEDIMENT AND RUNOFF ROUTING PROCEDURE
C        -ROUTING WOULD BE DONE FROM DOWNSLOPE TO UPSLOPE-
C
C
      OUTE=0.
      DO 502 KKK=1,KK
      DO 502 LLL=1,LL
      K=(KK+1)-KKK
      L=(LL+1)-LLL
```

```
      IF(MMM(K,L) .NE. 1) GO TO 502
      RUN=RUNO(K,L)
      CFAC=CFAA(K,L)
      IF(K .EQ. KK) GO TO 502
C
C      SET TIME EQUAL TO ZERO FOR ROUTING
C
      TFLOW=0.
      TIME=0.
C
C      FIND THE SLOPES AND DIRECTION THAT ROUTING WOULD BE CONDUCTED
C      ALONG THE RILL PATHS
C
400   IF(L .EQ. 1) GO TO 401
      GO TO 402
401   A1=(E(K,L)-E(K,L+1))/L1
      IF(A1 .LT.0.)A1=0.
      A2=(E(K,L)-E(K+1,L+1))/L2
      IF(A2 .LT. 0.)A2=0.
      A3=(E(K,L)-E(K+1,L))/L1
      IF(A3 .LT. 0.) A3=0.
      A4=0.
      A5=0.
      GO TO 406
402   IF(L .EQ. LL) GO TO 403
      GO TO 404
403   A1=0.
      A2=0.
      GO TO 405
404   A1=(E(K,L)-E(K,L+1))/L1
      IF(A1 .LT. 0.) A1=0.
      A2=(E(K,L)-E(K+1,L+1))/L2
      IF(A2 .LT. 0.) A2=0.
```

```
405   A3=(E(K,L)-E(K+1,L))/L1
      IF(A3 .LT. 0.) A3=0.
      A4=(E(K,L)-E(K+1,L-1))/L2
      IF(A4 .LT. 0.) A4=0.
      A5=(E(K,L)-E(K,L-1))/L1
      IF(A5 .LT. 0.) A5=0.
406   CONTINUE
      CALL BIG (A1,A2,A3,A4,A5,K,L,KK,LL,II)
      IF(II .EQ. 1) GO TO 481
      IF(II .EQ. 2) GO TO 482
      IF(II .EQ. 3) GO TO 483
      IF(II .EQ. 4) GO TO 484
      IF(II .EQ. 5) GO TO 485
481   SL=A1
      LE=L1
      GO TO 486
482   SL=A2
      LE=L2
      GO TO 486
483   SL=A3
      LE=L1
      GO TO 486
484   SL=A4
      LE=L2
      GO TO 486
485   SL=A5
      LE=L1
      GO TO 486
486   IF(SL .LE. 0.0) SL=0.00001
C
C      FIND THE FLOW TRAVEL TIME(TFLOW)FOR EACH SEGMENT OF RILL
C        -USE SUBROUTINE TRTI FOR THIS PURPOSE-
C
      CALL TRTI(CFAC,LE,SL,TFLOW)
```

```
C
C        DETERMINE THE FLOW RATE IN RILL SEGMENTS
C
       Q=(RUN)/(TFLOW*103680.)
       IF(Q .EQ. 0.)GO TO 888
C
C        DETERMINE THE DEPTH OF RILL FLOW
C        -USE SUBROURINE "NEW" FOR THIS PURPOSE-
C           --SET INITIAL DEPTH EQUAL TO 0.001 FT. --
C
       Y1=0.001
       CALL NEW(Y1,Q,SL,DD)
       GO TO 470
888    DD=0.
470    DEPTH=DD
       WIDTH=2*DEPTH
C
C        DETERMINE THE TRANSPORT CAPACITY OF RILL FLOW
C         -USE SUBROUTINE "YAL" FOR THIS PURPOSE-
C
       CALL YAL(DEPTH,SL,SG,US,VIS,TF1,Y,YCR)
       TF=TF1*TFLOW*60.*WIDTH
C
C        DETERMINE THE DETACHMENT CAPACITY OF RILL FLOW
C         -USE SUBROUTINE "DUB" FOR THIS PURPOSE-
C
       CALL DUB(DEPTH,SL,US,Y,YCR,DF1)
       DF=DF1*WIDTH*60.*TFLOW
C
C        FIND THE TOTAL DETACHED SOIL AVAILABLE FOR TRANSPORT
C
       DET=DF+EBP(K,L)+NET(K,L)
C
```

```
C       COMPARE THE TOTAL DETACHMENT WITH THE TOTAL TRANSPORT CAPACITY IN RILL
C
        IF(TF-DET) 489,489,490
489     TTF=TF
        GO TO 491
490     TTF=DET
        GO TO 491
491     IF(II .EQ. 1) GO TO 492
        IF(II .EQ. 2) GO TO 493
        IF(II .EQ. 3) GO TO 494
        IF(II .EQ. 4) GO TO 495
        IF(II .EQ. 5) GO TO 496
C
C       TRANSPOST THE NET RESULT TO THE NEXT SEGMENT OF RILL
C
492     EBP(K,L+1)=EBP(K,L+1)+TTF
        MK=K
        ML=L+1
        GO TO 497
493     EBP(K+1,L+1)=EBP(K+1,L+1)+TTF
        MK=K+1
        ML=L+1
        GO TO 497
494     EBP(K+1,L)=EBP(K+1,L)+TTF
        MK=K+1
        ML=L
        GO TO 497
495     EBP(K+1,L-1)=EBP(K+1,L-1)+TTF
        MK=K+1
        ML=L-1
        GO TO 497
496     EBP(K,L-1)=EBP(K,L-1)+TTF
        MK=K
        ML=L-1
```

```
      GO TO 497
497   IF(TF-DF) 501,501,498
498   IF(EBP(K,L) .GT. (TF-DF)) GO TO 500
      NET(K,L)=NET(K,L)-(TF-DF-EBP(K,L))
      IF(NET(K,L) .LT. 0.) NET(K,L)=0
      EBP(K,L)=0.
      GO TO 501
500   EBP(K,L)=EBP(K,L)-(TF-DF)
      GO TO 501
501   K=MK
      L=ML
      TIME=TFLOW+TIME
      IF(TIME .GE. TIM) GO TO 502
      IF(K .EQ. KK) GO TO 502
      GO TO 400
502   CONTINUE
      DO 504 K=1,KK
      DO 504 L=1,LL
      NET(K,L)=ABS(NET(K,L)+EBP(K,L))
504   CONTINUE
C
C       PRINT THE ROUTED ERODED SOIL
C
      PRINT 6000
      PRINT 6015
6015  FORMAT(' ',T40,'*      DTHE ERODED SOIL AFTER ROUTING         *')
      PRINT 6016
6016  FORMAT(' ',T40,'*                THE UNIT IS IN LBS            *')
      PRINT 6008
      DO 503 K=1,KK
      PRINT,' ROW NUMBER = ',K
      WRITE(6,6017)(NET(K,L),L=1,LL)
6017  FORMAT(' ',10F10.0)
```

```
      PRINT,' '
      PRINT,' '
      PRINT,' '
503   CONTINUE
C
C       FIND AND PRINT THE FINAL SCOUR OR DEPOSITION
C
      DO 505 K=1,KK
      DO 505 L=1,LL
505   FNET(K,L)=NET(K,L)-USLE(K,L)
      PRINT 6000
      PRINT 6018
6018  FORMAT(' ',T40,'*        THE FINAL SCOURE OR DEPOSITION      *')
      PRINT 6019
6019  FORMAT(' ',T40,'*   NEGATIVE=SCOURE , POSITIVE=DEPOSITION   *')
      PRINT 6020
6020  FORMAT(' ',T40,'*              THE UNIT IS IN LBS            *')
      PRINT 6008
      DO 506 K=1,KK
      PRINT,' ROW NUMBER = ',K
      WRITE(6,6021)(FNET(K,L),L=1,LL)
6021  FORMAT(' ',10F9.0)
      PRINT,' '
      PRINT,' '
      PRINT,' '
506   CONTINUE
      STOP
      END
C
C
C          THE END OF THE MAIN PROGRAM
C   ****************************************************************
```

```
C
C
C
C          SUBROUTINES USED IN THIS MODEL ARE;
C   *****************************************************************
C
C
      SUBROUTINE BIG(A1,A2,A3,A4,A5,K,L,KK,LL,III)
C
C      THIS SUBROUTINE SELECTS THE BIGGEST SLOPE AMONG THE FIVE SLOPES
C            --VARIABLES ARE,
C                 A1,A2,A3,A4,& A5=SLOPES
C                 K,L=THE ROW AND COLUMN POSITION OF THE GRID POINT
C                 KK,LL=THE TOTAL ROWS AND TOTAL COLUMNS RESPECTIVELY
C                 III=A PARAMETER WHICH INDICATES THE BIGGEST SLOPES
C
      IF(A1-A2) 10,70,38
10    IF(A2-A3) 11,18,28
11    IF(A3-A4) 12,15,15
12    IF(A4-A5) 105,104,104
15    IF(A3-A5) 105,103,103
18    IF(A3-A4) 19,22,25
19    IF(A4-A5) 105,104,104
22    IF(A3-A5) 105,103,103
25    IF(A3-A5) 105,103,103
28    IF(A2-A4) 29,32,35
29    IF(A4-A5) 105,104,104
32    IF(A4-A5) 105,34,34
34    IF(K .LT. KK/2)THEN DO
      IF(L .LT. LL/2)THEN DO
      GO TO 104
      ELSE DO
      GO TO 102
      END IF
      ELSE DO
      IF(L .LT. LL/2) THEN DO
      GO TO 102
```

```
        ELSE DO
        GO TO 104
        END IF
        END IF
35      IF(A2-A5) 105,102,102
38      IF(A1-A3) 39,49,59
39       IF(A3-A4) 40,43,46
40      IF(A4-A5) 105,104,104
43      IF(A3-A5) 105,103,103
46      IF(A3-A5) 105,103,103
49      IF(A3-A4) 50,53,56
50      IF(A4-A5) 105,104,104
53      IF(A3-A5) 105,103,103
56      IF(A3-A5) 105,103,103
59      IF(A1-A4) 60,63,66
60      IF(A4-A5) 105,104,104
63      IF(A1-A5) 105,104,104
66      IF(A1-A5) 105,68,101
68      IF(L .LT. LL/2)THEN DO
        GO TO 101
        ELSE DO
        GO TO 105
        END IF
70      IF(A2-A3) 71,91,81
71      IF(A3-A4) 72,75,78
72      IF(A4-A5) 105,104,104
75      IF(A3-A5) 105,103,103
78      IF(A4-A5) 105,103,103
81      IF(A2-A4) 82,85,88
82      IF(A4-A5) 105,104,104
85      IF(A2-A5) 105,34,34
88      IF(A2-A5) 105,102,102
91      IF(A3-A4) 92,95,98
92      IF(A4-A5) 105,104,104
95      IF(A3-A5) 105,103,103
```

```
98     IF(A3-A5) 105,103,103
101    III=1
       GO TO 110
102    III=2
       GO TO 110
103    III=3
       GO TO 110
104    III=4
       GO TO 110
105    III=5
       GO TO 110
110    CONTINUE
       RETURN
       END
C
C
C
C
```

```
C  ******************************************************************
      SUBROUTINE COOL(P1,T1,D1,B1,RST1)
C
C        THIS SUBROUTINE DETERMINES THE "R" VALUE TO BE USE IN USLE
C           COOLEY'S APPROACH IS USED IN THIS SUBROUTINE
C             --VARIABLES ARE,
C                   P1=TOTAL AMOUNT OF STORM(INCHES)
C                   T1=TOTAL STORM DURATION(HOURS)
C                   D1,B1=STORM DEPENDENT COEFFICIENTS
C                   RST1="R" FACTOR IN USEL
C
      POW=2.119*T1**0.0086
      RN=D1*P1*POW
      RD=T1**B1
      RST1=RN/RD
      RETURN
      END
C
C
C
C
```

```
C  *********************************************************************
      SUBROUTINE MEY(SS1,DL1,SLS1)
C
C       THIS SUBROUTINE DETERMINES THE "LS" FACTOR TO BE USED IN USLE
C
C                 --VARIABLES ARE,
C                        SS1=SLOPE STEEPNESS
C                        DL1=LENGTH (FT.)
C                        SLS1="LS" FACTOR
C
      SH=0.0076+0.0053*SS1+0.00076*SS1**2
      SLS1=ABS(SH*DL1**0.50)
      RETURN
      END
```

```
C     ******************************************************************
           SUBROUTINE TRTI(CI,LI,SI,TI)
C
C            THIS SUBROUTINE DETERMINES THE FLOW TRAVEL TIME IN RILL SEGMENT
C             -FEDERAL AVIATION AGENCY'S EQUATION IS USED-
C
C                   --VARIABLES ARE,
C                         CI=C-COEFFICIENT
C                         LI=RILL LENGTH (FT.)
C                         SI=RILL SLOPE
C                         TI=TRAVEL TIME (MINUTES)
C
           REAL LI
           PSI=SI*100.
           TI=(1.1-CI)*1.8*LI**0.50/(PSI**0.3334)
           RETURN
           END
C
C
C
C
```

```
C   ******************************************************************
      SUBROUTINE NEW(Y1,Q,SL,D)
C
C       THIS SUBROUTINE HELPS TO SOLVE THE NONLINEAR EQUATION
C       RESULTING FROM MANNING'S EQUATION
C         -NEWTON'S APPROACH IS USED IN THIS PART-
C
C             --VARIABLES ARE;
C                    Y1=INITIAL ESTIMATE OF FOLW DEPTH(FT.)
C                    Q=RILL FLOW RATE (CFS)
C                    SL=SLOPE STEEPNESS
C                    D=THE RILL FLOW DEPTH (FT.)
C
      Q1=0.745*SL**0.50
487   FA=(Q1*Y1**2.6667)-(Q*(0.01*Y1+0.018))
      FDA=2.6667*Q1*Y1**1.6667-0.01*Q
      FAFDA=FA/FDA
      Y2=Y1-FAFDA
      IF(ABS(Y2-Y1) .LE. 0.02) GO TO 488
      Y1=ABS(Y2)
      GO TO 487
488   D=Y1
      RETURN
      END
C
C
C
C
```

```
C   ****************************************************************
         SUBROUTINE TRICK(I,T1,IF)
C         THIS SUBROUTINE FINDS THE CORRECTED INFILTRATION
C         FROM THE EXPERIMENTAL INFILTRATION
C          --TRICKER EQUATION IS USED HERE
C         ---- VARIABLES ARE--
C                I=THE CUMULATIVE INFILTRATION(IN)
C                T1=TIME DURATION OF THE RAINFALL(SEC)
C                IF=THE CORRECTED CUMULATIVE INFILTRATION(IN)
        REAL I,T1,IF,IC,IE
        IE=(I*91440)/T1
        IC=(3.74)*(IE**0.46)*((T1/3600)**(-.64))
        IF=(IC*T1)/91440.
        RETURN
        END
```

```
C  ***************************************************************
      SUBROUTINE YAL(DEP,SL,SG,US,VIS,TCF,Y,YCR)
C
C       THIS SUBROUTINE DETERMINES THE TRANSPORT CAPACITY OF RILL FLOW
C         -YALIN'S EQUATION IS USED FOR THIS PURPOSE-
C
C            --VARIABLES ARE;
C                       DEP=RILL FLOW DEPTH(FT.)
C                       SL=SLOPE STEEPNESS
C                       SG=SPECIFIC GRAVITY OF SOIL
C                       US=PARTICLE DENSITY
C                       VIS=RUNOFF VISCOSITY
C                       TCF=TRANSPORT CAPACITY OF RILL FLOW
C                       Y=SHEAR STRESS
C                       YCR=CRITICAL SHEAR STRESS
C
      REAL NM
      WID=2*DEP
      NM=0.018+0.01*DEP
      DIA=(NM/0.034)**6.
      HR=DEP/(8**0.50)
C
C         GRAVITY ACCELERATION IS CONSIDERED TO BE 32.2 FT/SQ. SEC.
C         RUNOFF DENSITYIS SET TO BE 1.98
C         SPECIFIC WEIGHT OF RUNOFF IS CONSIDERED TO BE 1.0
C
      V=(32.2*HR*SL)**0.50
      Y=(V**2.)/((1.6500)*32.2*DIA)
      XX=DIA*(((US*1.98-1.98)*32.2)/(1.98*VIS**2.))**0.3334
      YY=(XX**0.92)/13.2
      YYC=YY*((VIS**2.)*(((US*1.98-1.98)*32.2)**2.)*1.98)**0.3334
```

```
      YCR=(YYC)/(1.65*32.2*DIA)
      IF(Y .LT.YCR)THEN DO
      DEL=0.
      ELSE DO
      DEL=(Y-YCR)/YCR
      END IF
      AA=(2.45)*((SG)**(-.40))*(YCR**0.5)
      SIG=AA*DEL
      IF(DEL .EQ. 0.) SIG=0.001
      TCF=1.98*(SG)*DIA*V*32.2*0.635*DEL*(1-(ALOG10(1+SIG))/SIG)
      RETURN
      END
C
C
C
```

```
C   *****************************************************************
          SUBROUTINE DUB(DEP,SL,US,Y,YCR,DCF)
C
C           THIS SUBROUTINE DETERMINES THE DETACHMENT CAPACITY OF RILL FLOW
C             -DUBOY'S PRINCIPAL IS USED HERE-
C
C                 --VARIABLES ARE;
C                        DEP=RILL FLOW DEPTH (FT.)
C                        SL=SLOPE STEEPNESS
C                        US=PARTICLE DENSITY
C                        Y=FLOW SHEAR STRESS
C                        YCR=CRITICAL SHEAR STRESS
C                        DCF=DETACHMENT CAPACITY OF RILL FLOW
C
          REAL NM
          NM=0.018+0.01*DEP
          DIA=(NM/0.034)**6.
          HR=DEP/(8**0.50)
C
C           FIND THE RILL FLOW VELOCITY FROM MANNING'S FORMULA
C
          VEL=(1.49/NM)*(HR**0.6667)*(SL**0.5)
          DCF=(10*VEL)*(Y**2.-Y*YCR)/((DIA)*(US-1.0)*62.5)
          RETURN
          END
C
C
C
C
```

```
C  ***************************************************************
      SUBROUTINE SLOPES(K,L,KK,LL,E,L1,L2,A1,A2,A3,A4,A5,AS)
C
C       THIS SUBROUTINE CALCULATES THE SLOPES IN THE FIVE DIRECTIONS
C       SURROUNDING A POINTS AND THEIR AVERAGE
C
C           --VARIABLES ARE;
C                 K,L=THE ROW AND COLUMN POSITION OF THE GRID POINT
C                 KK,LL=THE TOTOAL NUMBER OF ROWS AND COLUMNS
C                 E=ELEVATION
C                 L1=THE HORIZONTAL DISTANCE BETWEEN GRID POINTS(FT.)
C                 L2-DISTANCE BETWEEN GRID POINTS(FT)AT 45 DEGREE ANGLE
C                 A1, A2, A3, A4, A5=SLOPES STEEPNESS
C                 AS=AVERAGE OF SLOPES
      REAL L1,L2
      DIMENSION E(50,50)
      IF(K .EQ. KK) GO TO 12
      IF(L .EQ. 1) THEN DO
      A1=(E(K,L)-E(K,L+1))/L1
      IF(A1 .LT. 0.) A1=0.
      A2=(E(K,L)-E(K+1,L+1))/L2
      IF(A2 .LT. 0.) A2=0.
      A4=0.
      A5=0.
      GO TO 11
      ELSE DO
      IF(L .EQ. LL) THEN DO
      A1=0.
      A2=0.
10    A4=(E(K,L)-E(K+1,L-1))/L2
      IF(A4 .LT. 0.) A4=0.
      A5=(E(K,L)-E(K,L-1))/L1
      IF(A5 .LT. 0.) A5=0.
```

```
      GO TO 11
      ELSE DO
      A1=(E(K,L)-E(K,L+1))/L1
      IF(A1 .LT. 0.) A1=0.
      A2=(E(K,L)-E(K+1,L+1))/L2
      IF(A2 .LT. 0.) A2=0.
      GO TO 10
      END IF
11    A3=(E(K,L)-E(K+1,L))/L1
      IF(A3 .LT. 0.) A3=0.
      END IF
C
C        FIND THE AVERAGE
C
      AS=(A1+A2+A3+A4+A5)/5.
      GO TO 14
12    AS=ABS(E(K,L)-E(K-1,L)/L1)
14    CONTINUE
      RETURN
      END
C
C
```

```
C          START OF INPUT DATA
C  *********************************************************************
//DATA.INPUT DD *

 L1 T1 RR KK LL P T D B TIM US VIS SG

 E(1,1) E(1,2) E(1,3) ........................ E(1,LL)   ]
 E(2,1) E(2,2) ............................... E(2,LL)   ]
 .....................................................    ]--> Elevation Data
 .....................................................    ]
 E(KK,1) E(KK,2) E(KK,3) .................... E(KK,LL)   ]

 S(1,1) S(1,2) ............................... S(1,LL)   ]
 .....................................................    ]--> Sorptivity Data
 S(KK,1) S(KK,2) ............................ S(KK,LL)   ]

 A(1,1) A(1,2) ............................... A(1,LL)   ]
 .....................................................    ]--> A-Values Data
 A(KK,1) A(KK,2) ............................ A(KK,LL)   ]

 C(1,1) C(1,2) ............................... C(1,LL)   ]
 .....................................................    ]--> Cover Factor Data
 C(KK,1) C(KK,2) ............................ C(KK,LL)   ]

 KE(1,1) KE(1,2) ............................ KE(1,LL)   ]
 .....................................................    ]--> Soil Erodibility Data
 KE(KK,1) KE(KK,2) ......................... KE(KK,LL)   ]

 PP(1,1) PP(1,2) ............................ PP(1,LL)   ]
 .....................................................    ]--> Practice Management Factor
 PP(KK,1) PP(KK,2) ......................... PP(KK,LL)   ]      Data
```

APPENDIX B

SAMPLE PROBLEM OF INPUT AND OUTPUT FOR KEM

I. Required Input Data for KEM

1. Elevation
2. K (Soil Erodibility)
3. C (Ground Cover Factor)
4. P (Practice Management Factor)
5. S (Soil Sorptivity)
6. A-value (A Soil Property Factor)
7. Subwatershed Size
8. Total Amount of Rain (Or Average Rainfall Intensity)
9. Storm Duration
10. Air Temperature

II. Example Problem for a 10 x 10 Grid System (100 Subwatersheds)

Li = 10 ft

Ti = 1800 sec

RR = 0.03 in/sec

KK = 10

LL = 10

P = 0 (zero if total amount of rain is not known)

T = 0.5 hrs

D = 15.03

B = 0.5780

TIM = 30 minutes

US = 2.65

VIS = 12 x 10^{-6} ft^2/sec

SG = 2.65

The above information and other data for grid points in the computer format follow.

Note: Free format has been used for all input data.

```
C
C            START OF INPUT DATA
C   *****************************************************************
//DATA.INPUT DD *
10.   1800.0   0.03  10  10  0. 0.5  15.03  0.5780 30. 2.65  0.000012 2.65
70   70   70   70   70   70   70   70   70   70
70   65   60   70   70   70   65   70   70   70
60   65   55   60   60   55   55   60   60   70
60   55   50   45   60   50   60   60   50   60
60   60   60   40   50   40   50   40   50   50
50   50   40   35   40   40   35   40   40   40
50   45   40   35   30   30   30   35   35   35
45   45   40   35   30   30   25   30   35   35
40   40   40   30   25   20   30   30   30   30
30   30   30   30   25   20   20   20   20   20
```

Elevation Data

```
.1   .2   .2   .8   .8   .8   .2   .1   .8   .8
.8   .8   .8   .2   .1   .2   .8   .8   .8   .1
.1   .8   .8   .2   .8   .8   .8   .8   .8   .2
.2   .8   .8   .8   .8   .8   .8   .2   .8   .2
.8   .2   .2   .8   .8   .8   .2   .8   .8   .8
.1   .2   .8   .8   .2   .2   .8   .8   .1   .2
.8   .8   .8   .8   .8   .2   .8   .8   .8   .2
.8   .8   .1   .2   .8   .2   .8   .8   .2   .8
.8   .2   .8   .8   .8   .8   .2   .2   .8   .8
.2   .8   .8   .8   .8   .8   .8   .8   .8   .8
```

Sorptivity Data

```
.01  .02  .02  .08  .08  .08  .02  .01  .08  .08
.08  .08  .08  .02  .01  .02  .08  .08  .08  .01
.01  .08  .08  .02  .08  .08  .08  .08  .08  .02
.02  .08  .08  .08  .08  .08  .08  .02  .08  .02
.08  .02  .02  .08  .08  .08  .02  .08  .08  .08
.01  .02  .08  .08  .02  .02  .08  .08  .01  .02
.08  .08  .08  .08  .08  .02  .08  .08  .08  .02
.08  .08  .01  .02  .08  .02  .08  .08  .02  .08
.08  .02  .08  .08  .08  .08  .02  .02  .08  .08
.02  .08  .08  .08  .08  .08  .08  .08  .08  .08
```

A-Values Data

.3	.3	.3	.3	.3	.3	.3	.3	.3	.3
.3	.3	.3	.3	.3	.3	.3	.3	.3	.3
.3	.3	.3	.3	.3	.3	.3	.3	.3	.3
.3	.3	.3	.3	.3	.3	.3	.3	.3	.3
.3	.3	.3	.3	.3	.3	.3	.3	.3	.3
.3	.3	.3	.3	.3	.3	.3	.3	.3	.3
.3	.3	.3	.3	.3	.3	.3	.3	.3	.3
.3	.3	.3	.3	.3	.3	.3	.3	.3	.3
.3	.3	.3	.3	.3	.3	.3	.3	.3	.3
.3	.3	.3	.3	.3	.3	.3	.3	.3	.3

→ Cover Factor Data

.4	.4	.4	.4	.4	.4	.4	.4	.4	.4
.4	.4	.4	.4	.4	.4	.4	.4	.4	.4
.4	.4	.4	.4	.4	.4	.4	.4	.4	.4
.4	.4	.4	.4	.4	.4	.4	.4	.4	.4
.4	.4	.4	.4	.4	.4	.4	.4	.4	.4
.4	.4	.4	.4	.4	.4	.4	.4	.4	.4
.4	.4	.4	.4	.4	.4	.4	.4	.4	.4
.4	.4	.4	.4	.4	.4	.4	.4	.4	.4
.4	.4	.4	.4	.4	.4	.4	.4	.4	.4
.4	.4	.4	.4	.4	.4	.4	.4	.4	.4

→ Soil Erodibility Data

1	1	1	1	1	1	1	1	1	1
1	1	1	1	1	1	1	1	1	1
1	1	1	1	1	1	1	1	1	1
1	1	1	1	1	1	1	1	1	1
1	1	1	1	1	1	1	1	1	1
1	1	1	1	1	1	1	1	1	1
1	1	1	1	1	1	1	1	1	1
1	1	1	1	1	1	1	1	1	1
1	1	1	1	1	1	1	1	1	1
1	1	1	1	1	1	1	1	1	1

→ Practice Management Factor Data

III. Selected Output for Example Problems

```
*********************************************
*   THE FOLLOWING CHART SHOWS THE START OF     *
*   RILLS (AS *) AND THE RILLS PATTERNS (AS 1) *
*   AND THE EROSION CONTRIBUTING AREAS TO THE  *
*   RILLS (AS 8).  ZEROS ARE THE OTHER ZONES   *
*********************************************
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****8***88
*11***1***
1*1**11*1*
*111*1**1*
***1*1*1**
1*11**1*11
8111111811
08881811*1
0000818811
0000818811
```

THE ERODED SOIL AVAILABLE ALONG THE RILLS
((((THE UNIT IS IN LBS))))

FOR ROW NO. 1	370.	2574.	3150.	1043.	0.	370.	608.	370.	0.	0.
FOR ROW NO. 2	5554.	4064.	608.	21009.	11733.	21009.	6748.	16016.	4814.	1077.
FOR ROW NO. 3	370.	22599.	2574.	11221.	8058.	608.	370.	2574.	1858.	17408.
FOR ROW NO. 4	608.	608.	2574.	608.	57179.	1858.	33839.	28466.	1043.	11221.
FOR ROW NO. 5	4780.	14681.	59783.	608.	33023.	370.	35010.	370.	17408.	4780.
FOR ROW NO. 6	370.	7662.	1422.	370.	10109.	12893.	1422.	6748.	2574.	1422.
FOR ROW NO. 7	0.	11087.	6515.	6515.	34.	370.	608.	0.	370.	34.
FOR ROW NO. 8	0.	0.	0.	0.	12239.	0.	18975.	608.	4780.	1422.
FOR ROW NO. 9	0.	0.	0.	0.	0.	36234.	0.	0.	9054.	4780.
FOR ROW NO. 10	0.	0.	0.	0.	0.	33432.	0.	0.	54840.	36201.

THE ERODED SOIL AFTER ROUTING
THE UNIT IS IN LBS

ROW NUMBER										
1	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
2	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
3	1013.	1194.	0.	0.	0.	10131.	1274.	0.	0.	0.
4	0.	0.	0.	0.	24830.	0.	3745.	0.	0.	0.
5	0.	0.	10089.	0.	11618.	11032.	0.	51397.	0.	0.
6	239.	0.	48486.	59249.	0.	0.	0.	0.	9663.	0.
7	0.	0.	0.	0.	150117.	8206.	0.	0.	3230.	6426.
8	0.	0.	0.	0.	0.	0.	16308.	0.	0.	0.
9	0.	0.	0.	0.	0.	201650.	0.	0.	0.	0.
10	0.	0.	0.	0.	0.	33432.	0.	0.	68904.	43069.

THE FINAL SCOURE OR DEPOSITION
NEGATIVE=SCOURE , POSITIVE=DEPOSITION
THE UNIT IS IN LBS

ROW NUMBER										
1	-370.	-2574.	-3150.	-1043.	0.	-370.	-608.	-370.	0.	0.
2	-5554.	-4064.	-608.	-21009.	-11733.	-21009.	-6748.	-16016.	-4814.	-1077.
3	643.	-21406.	-2574.	-11221.	-8058.	9523.	904.	-2574.	-1858.	-17408.
4	-608.	-608.	-2574.	-608.	-32349.	-1858.	-30094.	-28466.	-1043.	-11221.
5	-4780.	-14681.	-49694.	-608.	-21406.	10662.	-35010.	51028.	-17408.	-4780.
6	-131.	-7662.	47065.	58880.	-10109.	-12893.	-1422.	-6748.	7090.	-1422.
7	0.	-11087.	-6515.	-6515.	150083.	7836.	-608.	0.	2860.	6392.
8	0.	0.	0.	0.	-12239.	0.	-2667.	-608.	-4780.	-1422.
9	0.	0.	0.	0.	0.	165415.	0.	0.	-9054.	-4780.
10	0.	0.	0.	0.	0.	0.	0.	0.	14064.	6968.

TECHNICAL REPORT DATA

(Please read Instructions on the reverse before completing)

1. REPORT NO	2.	3. RECIPIENT'S ACCESSION NO.
4. TITLE AND SUBTITLE Rill-interrill erosion and deposition model of stripmine hydrology		5. REPORT DATE 6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) M. R. Khanbilvardi, A. S. Rogowski, and A. C. Miller		8. PERFORMING ORGANIZATION REPORT N 2
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15. SUPPLEMENTARY NOTES

This project is part of the EPA-planned and coordinated Federal Interagency Energy/Environment R&D Program.

16. ABSTRACT

An erosion-sediment yield model (labeled KEM) was developed from the continuity consideration for sediment transport and from equations describing rill and interrill erosion. This computerized model is based on dividing the upland areas into a grid containing rill and interrill zones and on the Universal Soil Loss Equation (USLE). The USLE is used to estimate the sediment contribution from the interrill areas. Prediction of soil loss from the interrill areas is based on the premise that both raindro impact and overland flow energy can create soil erosion. The rill flow carries the interrill erosion along with the rill scour. Rill transport capacity governs the amount of removed soil from the site. If the flow transport capacity is less than the available eroded soil, net erosion equals the transport capacity and the excess sediment is deposited in the flow paths. Otherwise, all eroded soil will move downslope and out of the watershed.

The model was tested by simulating actual events on a small watershed in Central Pennsylvania for summer storms during 1981. Applying the model to this stripmined and reclaimed area created a set of information about the location and amount of watershed erosion and deposition. The areal distribution of erosion and deposition was compared with measured data. The model performed satisfactorily in predicting soil loss from the site.

17. (Circle One or More) KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS			b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Ecology Environments Earth Atmosphere Environmental Engineering Geography Other:	Hydrology Limnology Biochemistry Earth Hydrosphere Combustion Refining	Energy Conversion Physical Chemistry Materials Handling Inorganic Chemistry Organic Chemistry Chemical Engineering		6F 8A 8F 8H 10A 10B 7B 7C 13B

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