1972

Digital simulation of sheet erosion

Wilfredo Pineda David

Iowa State University

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Digital simulation of sheet erosion

by

Wilfredo Pineda David

A Dissertation Submitted to the
Graduate Faculty in Partial Fulfillment of
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CHAPTER I. INTRODUCTION

Soil erosion is a major problem today. Bennett (1939) estimated that approximately 3 billion tons of soil was washed out of the fields and pastures in the United States in 1939. Williams (1967) estimated 4 billion tons in 1967.

Not only is soil lost, but that carried by water contains higher proportions of plant nutrients, organic matter, and finer materials than are found in the original soil. The nutrient carrying sediments pollute streams and rivers. Reservoirs and ponds built for flood control, water supply, and recreation are reduced in capacity and in water quality.

The severity of the erosion problem is gradually being recognized by the nonagricultural public sector which is demanding control through legislative actions. Accurate estimates of the pattern of sediment movement from the fields into the larger streams are essential for the effective administration of legislative controls.

Objectives

The primary objective of this study is to develop a digital model of soil erosion by water. Specifically, this will involve:

(a) The development of a digital model to simulate the process of sheet erosion by water.
(b) The superimposition of the digital erosion model on a working mathematical watershed model.

(c) The application of the model to a small test watershed in order to evaluate its feasibility.
CHAPTER II. REVIEW OF LITERATURE

Sheet erosion is the product of the raindrop impact and overland flow. The distinctive actions of the raindrops and overland flow derive from the different directions in which their forces are applied to the land surface. Raindrops strike the soil surface from nearly a vertical direction. The impact of raindrops breaks down soil aggregates and splashes soil particles into the air, thus producing soil detachments known as splash erosion.

When the rate of rainfall exceeds the intake capacities of the soil, water that is not absorbed where it falls moves over the land surface as overland flow. It gains speed as it moves downslope and it also dislodges and transports soils. This process by which water sets soil in motion is known as scour erosion. In this study splash and scour erosion will be jointly taken as sheet erosion. Furthermore, sheet erosion will be defined to include both sheet and rill erosion.

Splash Erosion

More than 20 years ago, Ellison (1947) defined soil erosion as a process of detachment and transportation of soil materials by erosive agents. For erosion by water, these agents are rainfall and runoff. He pointed out that each has a detaching and transporting capacity, and that these must be studied separately. He suggested an approach to
erosion studies that would consider: (a) soil detachment by rainfall; (b) transport by rainfall; (c) detachment by runoff; and (d) transport by runoff as separate but interrelated phases of the process of soil erosion by water.

The terminology used by various investigators has not been consistently defined. Many investigators refer to soil splash loss as the amount of soil collected on soil traps after a given rainfall. Thus soil splash refers to the net amount of soil being translocated since the soil particles can move in and out of the soil traps. This concept of soil splash will be used in the following discussions. In addition, the term transport by rainfall will be used to describe the net amount of soil that is moved downslope toward the rill or channel system. Thus, on a flat, smooth slope the soil transport by rainfall is zero. Detachment by rainfall will be used to refer to the total amount of soil translocated. Detachment by rainfall then refers to the total amount of soil moving in and out of a given area.

Theoretically, the effect of rain splash is a function of the kinetic energy of raindrops. That is

\[
\text{Soil splash} = f(KE) = f(M V_T^2) \quad (2-1)
\]

where KE is the kinetic energy, \( M \) is the mass of raindrops, and \( V_T \) is the terminal velocity or the velocity with which the raindrops strike the soil. Since for any precipitation
duration, the mass is directly related to the accumulated depth, the theoretical kinetic energy may be calculated if the terminal velocities are known. Terminal velocities, however, vary with drop size and there is normally a spectrum of drop sizes in every storm (Mihara, 1951; Wischmeier and Smith, 1958). Furthermore, the energy transmitted by raindrops to the soil is influenced by many factors rendering the theoretical approach impractical for many field applications. Commenting on some of these factors, Ellison (1945) stated:

In soil and water conservation, the principal interest lies in determining the energy of raindrops that strike the soil. This may be a different problem from that of calculating the total energy of rainfall. Some of the drops are intercepted by plant residues and stones on the surface of the soil, while others may be intercepted by growing vegetation. The vegetal canopy may change storms and this may complicate the problem of comparing the effect of one storm with those of another. Often without change in the canopy, different amounts of interception will occur with different storms if a high wind drives them at an angle with the vertical. The same canopy may intercept less than 50 per cent of the drops if they fall vertically. In drilled crops with open canopies, the direction of the wind may affect the impact of raindrops on the surface of the soil. If the wind blows across the rows, most of the drops may be intercepted, but if the wind blows parallel to the rows, only a small percentage of the drops may be intercepted.

Several investigators have attempted to relate the physical characteristics of rainfall to soil splash. Laws (1940) observed a 1,200 per cent increase in the erosion rate when he increased the drop size from 1 to 5 millimeters. Mihara
(1951) reported soil splash as directly proportional to kinetic energy. Bisal (1960) shows detachment proportional to the 1.4 power of the drop velocity. Ekern (1951) shows splash proportional to the kinetic energy when the amount of applied water is constant. Rose (1960) reports that detachment is more closely related to momentum per unit area and time of rain than to the kinetic energy. Free (1960) found that splash losses from sand varied as the 0.90 power of the drop energy but to the 1.5 power of the drop energy for a silt-loam soil.

Ellison (1945) conducted studies in the effects of raindrop impacts on soil erosion using artificial rainfall on Muskingum silt-loam soil. He suggested the following relation between the quantities of soil splashed and rainfall characteristics

\[ E = K V^{4.33} d^{1.07} I^{0.65} \]  

(2-2)

where

- \( E \) = soil intercepted during a 30-minute period in grams
- \( V \) = velocity of drops in feet per second
- \( I \) = intensity of rainfall in inches per hour
- \( d \) = diameter of drops in millimeters
- \( K \) = soil constant

The quantities of soil splashed by raindrops were found to be very sensitive to either drop size or drop velocity.
These quantities were also affected by rainfall intensity and surface slope. Ellison found that 75 per cent of the splashed soil moved downhill and 25 per cent moved uphill on a 10 per cent slope.

Ekern and Muckenhirn (1947) found 60 per cent downslope and 40 per cent upslope movement of splashed sand on a 10 per cent slope. They suggested the relation where the relative downslope movement by splash is approximately equal to 50 per cent plus the per cent slope. This differential movement by vertical raindrops is explained by the fact that the downhill splash travels further before recontacting the soil surface. This is particularly important on steep slopes (Mihara, 1951). Wind effects in the field, however, may upset this pattern. Studies from oriented pans exposed to natural rainfall in New York showed three times more soil losses from pans facing the direction of the storm as from pans facing the opposite direction (Free, 1952).

Using four types of soil, namely, Darwin silty loam, Cisne silt loam, Flanagan silt loam, and Hegener loamy sand, Bubenzer and Jones (1970) studied the effects of drop size and impact velocity on the detachment of soils under simulated rainfall. Multiple regression techniques were used to relate soil splash to the rainfall characteristics for each of the four soils. Rainfall intensity and kinetic energy were found to be the best predictors of soil splash.
They derived the equation of the form:

$$SS = a (i)^S(Ke)^t$$  \hspace{1cm} (2-3)

where

- $SS =$ the amount of soil splash
- $i =$ rainfall intensity
- $Ke =$ kinetic energy
- $a =$ constant
- $s,t =$ constant exponents

The correlation coefficient obtained ranged from 0.92 for the Darwin silty clay to 0.96 for the Flanagan and Cisne silt loams. In each case, the correlation coefficient obtained for each of the separate soils was significantly better than the coefficient for all the soils combined. The prediction of soil splash for all soils was improved by adding a term containing the percentage clay to Equation (2-3).

An analysis of soil transportation by raindrop splash was made by Van Heerden (1967) using mass distribution curves. These curves were graphs showing the amounts of splashed soil received per unit area. They were determined experimentally by measuring the amounts of soil that splashed out of a source tray into collecting trays. With mass distribution curves, the loss or gain in splashed particles can be determined at any point within an area.

Since under normal field conditions neither the drop
velocity nor the drop diameter can be conveniently measured, investigations were directed towards finding functional relationships among the drop velocity, drop diameter, and rainfall intensity. Wischmeier and Smith (1958) by partly utilizing published information developed the equation

\[ E = 916 + 331 \log_{10} I \]  \hspace{1cm} (2-4)

where

- \( E \) = the kinetic energy in foot-tons per acre inch of rain
- \( I \) = rainfall intensity in inches per hour

They obtained a good index of soil loss per storm with the product \( E I_{30} \), where \( E \) is the total energy computed from Equation (2-4) and \( I_{30} \) is the maximum 30-minute intensity during the storm in inches per hour.

Mihara (1951) illustrated the relation between rainfall intensity and energy by the following equation

\[ E = A I^{1.20} \]  \hspace{1cm} (2-5)

where

- \( E \) = kinetic energy
- \( I \) = rainfall intensity
- \( A \) = soil constant
Scour Erosion

No soil erosion relationships commonly used to date distinguish between the rainfall splash and the overland flow subprocesses. The most commonly used soil loss equation estimates the combined sheet and rill erosion. The Agricultural Research Service of the USDA developed the so-called universal soil loss equation (Wischmeier and Smith, 1965), which has the form

\[ A = R K L S C P \]  

(2-6)

where

- **A** = average annual soil loss in tons per acre
- **R** = rainfall factor
- **K** = soil erodibility factor
- **LS** = length and steepness of slope factor
- **C** = cropping and management factor
- **P** = conservation practice factor

A soil loss equation similar in nature to Equation (6) which is much in use is the Musgrave's (1947) equation

\[ E = I \left[ \frac{R}{100} \right] \left[ \frac{S}{10} \right]^{1.35} \left[ \frac{L}{72.6} \right]^{0.35} \left[ \frac{P}{1.25} \right]^{1.75} \]  

(2-7)

where

- **E** = sheet and rill erosion in inches per year
\[ I = \text{erosion from continuous crop from a given soil (adjusted to 1.25 inches rainfall) in inches per year} \]

\[ R = \text{cover factor (fallow or continuous row crop equals 100)} \]

\[ S = \text{land slope in per cent (with 10\% as standard)} \]

\[ L = \text{length of the land slope in feet (with 72.6 feet as standard)} \]

\[ P = \text{is the maximum 30-minute rainfall amount, 2-year frequency, in inches (with 1.25 inches as standard)} \]

Equation (2-7) was later modified by Farnham, Beer, and Heinemann (1966) as follows:

\[ E = 0.59 \left( \frac{KR}{150} \right) \left( \frac{R}{100} \right) \left( S \right)^{1.35} \left( \frac{L}{72.6} \right)^{0.35} \quad (2-8) \]

where \( K, R, P \) are as defined in the universal soil loss equation, and the rest of the terms are as defined in Equation (2-7).

Gottschalk and Brune (1950) developed a method commonly known as TP-97. In this method, the average slope length is determined for the area in row crops and small grains. The predominant crop rotation is also determined. Tabulated values for soil losses from straight-row cultivation, contoured but not terraced, and contoured and terraced cropland are used to determine sheet erosion from cultivated croplands. These values are then adjusted for both the proportion of the watershed in clean-tilled row crops and predominant rotation. Sheet erosion from other sources are estimated at 350 tons
per square mile per year.

Beer, Farnham and Heinemann (1966) compared the universal soil loss, Musgrove modified, and the TP-97 methods of sheet erosion prediction. The results showed that both the universal and the Musgrave modified soil loss equations gave comparable results. The TP-97 method gave twice as much computed soil loss as the other two methods. Of all the three methods, the modified Musgrave equation gave the lowest coefficient of variation and the highest coefficient of regression.

It is to be noted that in all the sheet erosion prediction equations mentioned above, an explicit term representing overland flow is missing. Since the effect of runoff on sheet erosion is known to be very important, the prediction of sheet erosion with any of the above equations may lead to gross error when applied to specific time periods.

The specific role played by runoff in the sheet erosion process was studied by Ellison (1945). He found that soil loss caused by overland flow alone was related to the square of the velocities. The loss was initially very high but decreases rapidly with time. When rainfall was applied simultaneously with overland flow, a significant amount of soil loss increase was observed. Aggregate analysis showed that the material in the runoff was much finer than the material in the splash. This indicates that the coarser soil particles originally in the splash could not be
transported by the runoff and were deposited within the experimental plot.

The combined effects of raindrop energy and soil moisture on sheet erosion were investigated by Dragoun (1962). He used data from two small watersheds and found that the quantity of soil loss best correlated as follows:

\[ L_s = E I_{30} (1 + Pa - Qa) \]  

(2-9)

where

- \( L_s \) = the quantity of sediment transported in a particular storm
- \( Pa \) = antecedent precipitation for a five day period
- \( Qa \) = antecedent runoff for a five day period in inches
- \( E \) = total storm energy computed from Equation (2-4)
- \( I_{30} \) = the maximum 30-minute intensity during the storm in inches per hour

Podmore and Merva (1969) conducted a study to obtain information on the transport of thin materials by thin film flow. They introduced the critical distance of transport of particles by thin film flow concept and several models based on Stokes law settling through a laminar boundary layer were derived. Critical distance was defined as the distance from the point of insertion of sediment in the flowing film to the point at which a maximum amount of material is deposited for predetermined particle size range. The results showed that the critical distance is generally independent of the
particle size; decreases with increasing surface roughness; and generally increases with increasing slope for smooth surfaces while for very rough surfaces the opposite effect is found. They also found that Stokes law is not a satisfactory model of sediment transport mechanism.

Meyer and Monke (1965) studied the effects of slope steepness, slope length, particle diameter, and rainfall intensity on soil erosion by rainfall and overland flow using spherical glass beads. Their study showed that runoff erosion increased rapidly with increasing slope and length except at small slopes and lengths where essentially no erosion occurred. Rainfall plus runoff, as compared with runoff alone, increased the erosion of the small particles but decreased the erosion of the larger ones.

Runoff with rainfall caused greater erosion for the smaller particles but less erosion for larger particles as compared to the same runoff without rainfall. Increased sediment availability and runoff carrying capacity, due to raindrop-induced turbulence and splash, were more dominant for the more easily transported soil particles whereas decreased carrying capacity of the runoff due to decreased flow velocity from splash leveling of the soil bed and to raindrop-impact dissipation were dominant for the larger sizes.

A multiple regression analysis of the experimental data they obtained from trials where the slope steepness was 7 per
cent or greater gave the equation of best fit as:

\[ E_r = C (S - S_c)^{m'} (L - L_c)^{n'} D^{-0.5} \]  \hspace{1cm} (2-10)

where

- \( E_r \) = soil erosion by runoff per unit width
- \( C \) = constant
- \( L \) = slope length
- \( L_c \) = critical slope length or the slope length where \( E_r \) becomes zero for a given \( S \) and \( D \)
- \( S \) = slope steepness
- \( S_c \) = critical slope steepness or the slope steepness in which \( E_r \) is zero for a given \( L \) and \( D \)
- \( m' \) = constant exponent whose value range from 2.0 to 2.5
- \( n' \) = constant exponent approximately equal to 1.5
- \( D \) = sphere diameter

In a recent laboratory study, Foster and Martin (1969) investigated the effects of unit weight or bulk density of soil and slope on soil erosion. Their study showed that slope has an effect on the amounts of soil erosion and runoff. The effect of unit weight on the amount of soil erosion was significant only during the early time period. The effect of the slope-unit weight interaction was, however, significant at all time periods. The effect of unit weight on the volume of runoff was significant at all time periods. The effect of the unit weight-slope interaction on the volume of runoff...
water was also significant.

The findings of Foster and Martin (1969) on the relationship between the quantity of erosion and slope is not in complete agreement with those of Meyer and Monke (1965) who concluded that an increase in slope (without qualification as to the slope limits) results in an increase in soil loss. Foster and Martin (1969) showed that erosion occurring on a slope increased to a maximum and then decreased with further increases in slope. They concluded that for a given unit weight, there is a unique slope from which the maximum amount of erosion will occur, and vice versa.

Several studies have been made attempting to formulate mathematical equations expressing the capacity of flowing water to transport soil particles. Citing previous studies, Meyer and Monke (1965) stated that the tractive force of runoff increases as the runoff velocity squared; the quantity of sediment it can transport as the velocity to the fourth power; and the size of the particle it can move increases as the velocity to the fifth power. But as yet there is no generally accepted analytical theory or satisfactory experimental results defining the sediment transport capacity of overland flow. Excellent discussions on particle transport by fluid flow over a flat surface of loose grains are given by Raudkivi (1967) and Vanoni and his associates (1960).
Erosion Models

Soil erosion modeling is a relatively new method for the investigation of soil losses. This may be explained in part by the lack of satisfactory analytical expressions useful for evaluating some aspects of the erosion process. Also because of the complex nature of the erosion process, manual solutions needed for the projections and correlation of data are generally cumbersome and limited in scope. With the advent of the digital computers, the traditional limitation of calculating speed is removed and simulation methods that are greatly expanded in scope are now possible. Satisfactory digital models simulating many phases of the hydrologic processes related to the soil erosion process are now available.

Existing erosion equations have been used to calculate the effects of slope shape on soil loss. Working with plots of slope lengths of 75 feet, Onstad et al. (1966) developed a model based on the universal soil loss and continuity equations and routed it through slope intervals of 5 feet. Results obtained for different slope shapes under simulated rainfall conditions indicated that on the average there was no difference between predictions using the model and predictions made by simple calculations using the universal soil loss equation. This is to be expected since the model was based
on the universal soil loss equation and thus its accuracy is largely dependent on the latter. The results agreed with measured soil losses for wet and dry antecedent soil moisture conditions. Close inspection of their data, however, showed wide variations in accuracy for individual events.

Following the suggestion of Ellison (1947), Meyer and Wischmeier (1969) proposed a mathematical model to describe the process of soil erosion by water. Four subprocesses were considered and the relationships used in their models are as follows:

1. Detachment by rainfall, $D_r$

\[ D_r = f(e, i, c, g, a, s') \]

\[ D_r = e i \]

\[ E = i^{1.14} \]

\[ D_r = S_{dr} a i^2 \]

where

- $E =$ rainfall kinetic energy
- $S'$ - soil factor
- $C =$ watershed cover
- $I =$ rainfall intensity (maximum 30-minute intensity)
- $G =$ watershed geometry
- $A =$ area of increment
- $S_{dr} =$ a parameter that varies with $S$, $C$, and $G
2. Detachment by runoff, $D_f$

\[ D_f \propto \text{Ttractive force, } T \]
\[ T = kV^2 \]
\[ D_f \propto V^2 \]
\[ V^2 = S^{2/3} Q^{2/3} \]
\[ D_f = S_f A (S_u^{2/3} Q_u^{2/3} + S_l^{2/3} Q_l^{2/3})/2 \]

where

- $V$ = velocity of overland flow
- $Q$ = overland flow
- $k$ = constant
- $S$ = soil slope
- $S_f$ = soil factor
- $u,l$ = subscripts indicating upper and lower portions of the increment, respectively

3. Transport by rainfall, $T_r$

\[ T_r = f(S, I, S_p, G, U, C) \]

\[ T_r = S_t S I \]

where

- $U$ = wind factor
- $S_p$ = soil parameter
- $S_t$ = a parameter that varies with $U$, $C$, $S_p$, and $G$
4. Transport by runoff, $T_f$

$$T_f = k v^5$$

$$v = s^{1/3} Q^{1/3}$$

$$T_f = S_f s^{5/3} Q^{5/3}$$

where

$S_f = \text{soil factor and the rest of the terms are as defined above.}$

The above relationships were derived from empirical formulas and from some well known relationships in fluid mechanics. The study of Meyer and Wischmeier (1969) demonstrates two important concepts very relevant to erosion modeling:

1. Different processes are modeled separately allowing where possible, physical concepts to be used. The separate effects of these processes may be observed and varied independently.

2. The processes are separated into detachment and transport functions. These are then compared to determine whether it is sediment supply or sediment transport that is limiting, thus, predicting either erosion or deposition at a point on the profile.

Figure 1 shows the flow chart of the model simulating the process of soil erosion by water. The four erosion sub-processes are evaluated for each successive slope-length increment, and the soil movement is routed downslope as illustrated.

Following the development of the Stanford Watershed Model IV by Crawford and Linsley (1966), Negev (1967)
Figure 1. Flowchart of the model simulating the process of soil erosion by water. Four subprocesses, detachment by rain, detachment by runoff, transport by rain and transport by runoff are evaluated for each successive slope-length increment, and the soil movement is routed downslope as illustrated (Meyer and Wischmeier, 1969)
developed a sediment model on a digital computer. He superimposed his sediment model on the flow components of the watershed model. The sediment model distinguishes between the stream and the land surface. The stream surface is that part of the river channel system which includes rills and gullies while the land surface is the entire watershed excluding the stream surface. Figure 2 depicts the erosion and sedimentation processes as conceived by the model. Some of the relationships and concepts utilized by the model are explained below.

**Land surface**

As the raindrops hit the ground, soil particles of various sizes are splashed into the air. If overland flow is not taking place at that particular instant, all of the splashed particles will be deposited. If overland flow does occur, only the relatively coarser particles are deposited while the fine soil particles remain in suspension and are transported by the overland flow towards the nearest channel. The hourly quantity of fine soil particles produced by the splashed process (either transported by overland flow or redeposited) is computed in the model from the relation

\[ RER = KRER HPP(t) J_{RER} \]
Figure 2. The erosion and sediment transport processes as conceived by Negev (1967)
where

\[ \text{RER} = \text{hourly quantity of soil splash, tons} \]
\[ \text{HPP}(t) = \text{hourly rainfall during hour } t, \text{ inches} \]
\[ \text{KRER} = \text{a parameter that varies with soil type and cover} \]
\[ \text{JRER} = \text{an exponent} \]

The fine soil particles that had been detached by the raindrops but were deposited are left loosely on the ground. Upon the occurrence of the overland flow they may be picked up and added to the splashed soil that is already being transported. The hourly quantity of fine soil scoured in this process is computed by the relation

\[ \text{SER} = \text{KSER } \text{SRER}(t-1) \text{ OVQ}(t)^{\text{JSER}} \]

where

\[ \text{SER} = \text{hourly quantity of splash soil pickup, tons} \]
\[ \text{OVQ}(t) = \text{hourly overland flow during hour } t, \text{ inches} \]
\[ \text{KSER} = \text{a parameter that varies with soil type and surface roughness} \]
\[ \text{SRER}(t-1) = \text{the accumulated deposits of fine soil particles at the end of hour } t-1, \text{ tons} \]
\[ = \text{SRER}(0) + \sum_{t=0}^{t-1} (\text{RER OVQ}(t)=0 - \text{SER}) \]
\[ \text{SRER}(0) = \text{the quantity of loose fine particles available in the land surface prior to the rainy season, tons} \]
\[ \text{JSER} = \text{an exponent} \]
The hourly quantity of soil particles picked up from impervious surfaces such as roads, roofs, and rock outcrops is estimated as

$$E_{IM} = K_{IMP} \cdot R_{ER}$$

where

$$E_{IM} = \text{hourly quantity of sediment contributed from impervious surfaces, tons}$$

$$K_{IMP} = \text{a constant representing the ratio of the effective areas contributing to this process to the total watershed area}$$

The total quantity of fine soil particles that is transported into the stream by surface runoff during any hour is

$$W_{LA}(t) = R_{ER} + S_{ER} + E_{IM}$$

The wash load $W_{LA}(t)$ is hydraulically routed through the stream system using the Time-area method.

**Stream surface**

Overland flow is generally characterized by shallow depth and low velocities. Under such conditions the erosive power of the overland flow is small. Where conditions of excessive runoff, steeper slopes, and sparse vegetal cover exist, the overland flow may cause significant amount of soil erosion. Since in a natural watershed neither the flow depth nor the soil type and cover are uniform, this erosion
may tend to be more pronounced along certain paths of flow than others, resulting in the formation of rills. Rills may then enlarge to form gullies. The quantity of soil transported into the stream in this process is computed from the relation

\[
GER = KGER \cdot O V Q(t)^{JGER}
\]

where

- \(GER\) = hourly quantity of sediment contributed from rills and gullies, tons
- \(JGER\) = an exponent
- \(KGER\) = a parameter that varies with the characteristics of the land surface.

The various parameters are obtained by trial and error procedure using recorded hydrological data and, hence, the applicability of the model is limited to basins having accurate climatological data. Of particular importance is the rainfall intensity because of the important role it plays in the production of sediment. It is also an important input in the simulation of overland flow by the Stanford Watershed Model.

Rowlison and Martin (1971) proposed a rational model describing slope erosion. This model is very similar to that proposed earlier by Meyer and Wischmeier (1969). Both models consider the detachment and transport functions of both rainfall and runoff. Rowlison and Martin, however, qualitatively
evaluated the effects of slope and depth of water flow over the soil surface on the various erosion subprocesses in a laboratory experiment.

In the model they assumed that the detachment of soil due to runoff is negligible since the shearing stresses exerted by the flowing water are usually very small compared to the cohesive forces of most soils. A qualitative description of the soil detachment due to the rainfall impact is shown in Figure 3. Curve AB shows the general relationship between the detachment rate and the depth of the overland flow. The relationship between the detachment rate and slope is illustrated by curve AD which is for a given impact force. The interrelationship among the slope, detachment rate, and depth of overland flow is defined by the detachment rate surface ABCD.

Figure 4 shows the transportation rate surface as a function of slope and the depth of the overland flow. At zero depth of flow, the transportation rate which is due to rainfall alone is illustrated by curve EH. At zero slope there will be no overland flow and the net rainfall transportation will be zero as shown by line EF. The relationships between transportation rate versus depth of overland flow and transportation rate versus slope are assumed to be both exponential in nature as shown by curves HG and FG, respectively.
Figure 3. Potential detachment rate surface (Rowlison and Martin, 1971)

Figure 4. Potential transportation rate surface (Rowlison and Martin, 1971)
The rate that solid particles will erode from the soil surface will be controlled by the smaller of detaching capacity or transporting capacity. Stated another way, no more soil can be eroded than can be transported downslope. Using the limiting conditions, the surfaces of Figures 3 and 4 can be combined into one surface that defines the maximum erosion rate as a function of slope and the depth of the overland flow as shown in Figure 5.

As a summary, it should be mentioned that the models proposed by Rowlison and Martin (1971) and Meyer and Wischmeier (1969) were not published for sediment prediction but as research developments. They may be considered as qualitative hypotheses designed to serve as frameworks for quantitative models of soil erosion by water.
Figure 5. Surface of maximum erosion rate (Rowlison and Martin, 1971)
CHAPTER III. WATERSHED MODELING

Introduction

During the past 15 years, a very significant amount of effort has been directed toward hydrologic modeling. Some model builders have used an arrangement of analog components. Others have used a reduced scale laboratory replica of the natural system.

With the advent of high speed digital computers, comprehensive mathematical models in digital computer programs were made feasible. Such models are usually broad and complex and are usually dependent on previous works. Many workers have contributed ideas and methods that are influential in their developments. Background information on the developments of these models are given by Crawford and Linsley (1966), Haan (1967), DeBoer (1969), and Larson (1971).

Mathematical hydrologic models are of two general types - deterministic and stochastic. Stochastic models use the statistical properties of existing records and probability laws to generate future events. Very often, small agricultural watersheds have very limited hydrologic data. Those that have sufficient years of record are usually undergoing significant modifications. Their past records, therefore, cannot be used directly as bases for future predictions. For this reason, this study is concerned primarily with deterministic watershed models.
A deterministic watershed model represents the many hydrologic processes that occur in a watershed by a series of mathematical relationships. It consists of many component models, each representing a certain hydrologic process such as infiltration or evapotranspiration. For each unit of time, the individual components are used in combination to simulate moisture movement within, into, and out of the watershed.

The functional relationships describing a hydrologic process are of two general types which Larson (1971) referred to as physical and conceptual. Physical functions are based on a working knowledge of the actual process and are generally based on measurable parameters. Conceptual functions, on the other hand, are based on a knowledge of the processes which are related either physically or empirically to the actual process being represented. This often requires the use of watershed parameters which cannot be measured directly and, therefore, must be evaluated by fitting or trial and error.

One of the earliest and most widely used deterministic watershed model is the Stanford Watershed Model (SWM) developed by Crawford and Linsley (1966). It is a comprehensive and also a generalized model since it can be applied to different watersheds by changing the input parameters. As do all large and comprehensive watershed models, it has become almost a living entity as it is continuously developed to meet new needs. It is because of this high degree of flexibility that
a modified Stanford Watershed Model which is commonly referred to as the Kentucky Watershed Model (KWM) is used in this study.

The Kentucky Watershed Model

Crawford and Linsley (1962) published the original version of the Stanford Watershed Model (Mark II). The most widely publicized version (SWM IV) appeared in 1966 (Crawford and Linsley, 1966). The same Stanford group more recently developed a system called Hydrologic Simulation Programming incorporating a much more sophisticated routing technique capable of simulating simultaneous flows at a large number of points within the watershed.

The original version of the SWM was written in Burroughs computer language (BALGOL) used by the Stanford University Computer Center. In spite of its great potential, a number of factors have deterred its widespread use. Those frequently mentioned (Liou, 1970) are: programming in a little used computer language; difficulty in understanding the model as complicated by its bulk; unfamiliarity of many hydrologists with the digital modeling process; and the difficulty new users experience in acquiring the skill needed in estimating the numerous parameters required as input data.

Realizing these limitations, James (1970) and his associates at the University of Kentucky translated the
Stanford Watershed Model III as reported by Anderson and Crawford (1964) into Fortran IV, which because of the much more widespread use of the computer language, contributed toward increasing the model's use. Later, a number of improvements presented in the SWM IV were added along with other adaptations. They also made pioneering effort in developing a self-calibrating streamlined version of the model (OPSET) in order to eliminate the trial and error approach to parameter estimation. They called their SWM version the Kentucky Watershed Model (KWM) more to absolve the Stanford group of the blame for the differences rather than to deny them credit for original program development. Their work was reported in three parts. Liou (1970) reported the development of the self-calibrating version (OPSET) and provided program listings for both the OPSET and KWM. Ross (1970) gave detailed instructions on the use of both the KWM and OPSET. James (1970) evaluated the relationships between streamflow patterns and watershed characteristics through the use of OPSET.

The major elements of the SWM or KWM are shown on Figure 6. Precipitation and potential evapotranspiration are the main input data. Additional climatological data such as temperature, solar radiation, potential snow evaporation are used where snowfall is significant. The snowmelt simulation is modeled by the snowmelt subroutine whose major elements are shown on Figure 7.
Figure 6. Flowchart of the Stanford Watershed Model IV (Crawford and Linsley, 1966)
Figure 7. Stanford Watershed Model snowmelt subroutine flowchart (Anderson and Crawford, 1964)
The calculations begin from known or assumed initial moisture storage conditions and yield continuous simulation of the hydrologic cycle. Precipitation form is differentiated as to rain or snow. Depending on its form, precipitation may be stored in the snowpack and/or in the three major soil moisture storage categories shown on Figure 6. The model keeps an account of all incoming water until it leaves the watershed via evapotranspiration, streamflow, or subsurface flow.

The soil moisture and groundwater profiles are represented by the upper, lower, and the groundwater storage zones. The upper and lower storage zones regulate infiltration, overland flow, interflow, and inflow into the groundwater storage. The upper zone includes both interception and depression storages. Interception is governed by watershed cover and the current volume of interception in storage. The initial precipitation enters interception storage until a preassigned volume is filled. It continues during a storm as a result of evaporation losses which are assumed to occur at a corresponding potential evapotranspiration rate. Depression storage is governed by the watershed surface configurations. It is represented together with interception by a nominal upper zone storage level (UZC) and a watershed parameter which serves as an index of the degree to which UZC changes with time as a result of cultivation practices and
other factors.

The complex process of infiltration is modeled by a cumulative frequency distribution of infiltration capacity which represents a variable infiltration function over a watershed. As shown on Figure 8, this distribution is assumed to be linear from zero to a maximum value. It is also assumed that interflow is directly proportional to the infiltration capacity. Thus, the tendency for infiltrating water to become interflow is assumed to be directly proportional to the infiltration capacity.

The simulated reaction of a watershed to a given moisture supply, PEP, is shown on Figure 8. The incoming moisture is first subject to the operation of the cumulative infiltration capacity functions which govern interflow detention storage and the direct flow into the long term lower zone and ground water storages. The amount of moisture in surface detention which is subject to the operation of the upper zone storage is calculated.

The interflow distributions and the infiltration capacity at any given point and time are functions of the current lower zone storage and four watershed parameters. These parameters pertain to a nominal lower zone storage level (LZC), a basic maximum infiltration rate (BMIR), and interflow relative to overland flow factor (BIVF), and an index to the seasonal variation in the basic maximum infiltration rate.
CMIR = \frac{\text{CONSTANT} \times \text{SIAM} \times \text{BMIR}}{\text{FUNCTION (LZS/LZC)}}

\text{SIAM} = \text{FUNCTION (SIAC)}

\text{CIVM} = \text{BIVF} \times \text{FUNCTION (LZS/LZC)}

\text{LZS} = \text{Current value of lower zone moisture storage}

\text{PEP — 100\% of the watershed area with an infiltration capacity equal to or less than the indicated value}

Figure 8. Model for estimating infiltration capacity (Crawford and Linsley, 1966)
(SIAC). The above parameters are denoted by the symbols assigned to them in the program listing given on Appendix A in order to facilitate the understanding of the computer programs.

The quantity of net infiltration into the lower zone at any given time is determined by the current value of CMIR. Similarly, the current value of the product CMIR \times CIVM determines the time distribution of runoff by controlling the ratio of increments to surface detention leading to overland flow and interflow detention. As shown on Figure 8, the value of CMIR at any given time is a function of the basic maximum infiltration rate and the seasonal infiltration adjustment constant and the current value of the dimensionless ratio LZS/LZC. The same dimensionless ratio together with the parameter BIVF determine the current value of the variable CIVM. The various nonlinear relationships used to estimate CMIR and CIVM are based on empirical observations and are explained in details by Crawford and Linsley (1966). The value of CMIR decreases rapidly with the ratio LZS/LZC while that of CIVM increases gradually with the same ratio.

The water that remains in surface detention after direct infiltration is removed from the upper zone by evaporation, surface runoff, and delayed infiltration into the lower zone and groundwater storage. Evapotranspiration occurs from the upper zone storage at a potential rate.
The overland flow is modeled by means of a continuity equation relating the rate of discharge for overland flows to the volume of surface detention. The basic relationship for overland flow discharge rates is given in terms of the moisture supply rate, average amount of surface detention for a time interval, the amount of surface detention at equilibrium for a given supply rate, and the slope length and the surface roughness coefficient of the flow plane.

In the model, the groundwater supply rate is simulated directly at the mouth of the watershed. The sum of overland flow and interflow is simulated as channel inflow. The channel inflow is routed downstream to the gage point using a simple empirical routing technique. In this method a channel time-delay histogram is derived by planimetering contributing areas, estimating the channel flows at successive points in the stream channel system, and calculating the time of flow to the watershed outlet. The histogram is used to translate the channel water through a hypothetical reservoir.

**Operation of the Kentucky Watershed Model**

A program listing of the Kentucky Watershed Model together with the superimposed erosion model is given in Appendix A. By using the appropriate control options that are listed in Appendix B, the erosion model may be excluded from the
analysis. The watershed model portion is similar to that given by Liou (1970) except for some modification and adaptations to Iowa conditions.

Ross (1970) discusses the details of the operation of the KWM and lists typical input data. His report is intended to be a manual for understanding the many facets of programs use. Unfortunately, however, the KWM programs use a complicated subroutine to read input data. This subroutine is written in machine language to read input data punched in a free format, or format varying from one user to the next. The details of this subroutine are not covered in their reports and, hence, the program cannot be readily used. Furthermore, problems are usually encountered in trying to adapt this subroutine from one computer operation system to another.

Due to the above considerations, all the read statements were rewritten in convenient formats as shown in Appendix A. As a result of this and other program modifications, the operation of the model listed in Appendix A is somewhat different from that outlined by Ross (1970). Also, Ross did not use the snowmelt subroutine and, hence, it is not included in his discussions. Anderson and Crawford (1964), however, outlined the operation of the subroutine. To make full use of the above mentioned works, the following discussions attempt to be consistent with those of Ross and Anderson and Crawford wherever possible.
Input data

The required input data for the program listed in Appendix A are of six general types:

1. Control options that specify the type of input and output for a particular run.

2. Watershed parameters. These include the time-delay histogram as well as the general physical parameters, land surface parameters, and channel system parameters required by both the KWM and the superimposed erosion model.

3. Input data indicating the dates during the water year in which some parameters are in effect. These also include the dates when pan evaporation measurements are discontinued in late fall and started again in early spring. Such dates usually vary from one water year to another.

4. Input data describing climatological events.

5. Input data describing initial moisture conditions prevailing at the start of the first year to be synthesized.

6. Input data indicating the daily amounts of streamflow, diversion, and suspended sediment loads.

The input data relating to the erosion model will be discussed more in details in the following chapters. Those that pertain to the KWM are briefly discussed below.

Control options

Twenty control options are available in the model. Of these, only the first sixteen are working options as the last four are reserved for future program expansion. Each of the sixteen options are explained in Appendix B. Options 1, 4, 5, 6, and 14 provide the user with the opportunity to request additional output.
Option 2 allows the user to divide the hourly rainfall among 15-minute periods following a typical storm distribution rather than divide it equally. This option calls a subroutine PREPRD into action and divides hourly precipitation into a distribution described by Liou (1970). It is normally used only for small watersheds having times of concentration of less than one hour where the 15-minute distributions of rainfall can have a very significant effect on the flood peaks.

Options 3, 8, 9, 11, and 16 provide flexibility in using various types of input data depending on available records. Option 9 is normally used if streamflow records are available. Where such records are lacking, options 4, 14, 15, and 16 cannot be exercised. Option 15 specifies if the erosion model is to be included in the analysis. Obviously, option 16 cannot be used if option 15 is not in effect.

Option 7 calls into action the snowmelt subroutine. This option is used where snowmelt is significant. To use this option, additional input data such as those shown in Figure 7 are needed.

Option 10 is used when two different watersheds are synthesized in the same computer run. Option 12 offers the user the choice of a fifteen or sixty minute channel routing time increment. The time-delay histogram must correspond accordingly to the option taken. Option 13 provides a means
for making the time routing of storm hydrographs nonlinear by causing the flow to move downstream faster during periods of higher flows.

Watershed parameters

The watershed parameters required by the KWM may be divided into two general types: 1) measurable parameters or those parameters that can be reasonably estimated from observed watershed characteristics and 2) parameters that have to be fitted or estimated through the comparison of observed and predicted statistics.

The measurable parameters are:

1. BDDFSM is the basic degree hour factor (in/hr).
2. ELDIF is the elevation difference (thousand feet) from the base temperature gage location to the mean elevation of the watershed.
3. XDNFS is the index to the density of new fallen snow.
4. AREA is the total area of the watershed (square miles).
5. FIMP is the fraction of the watershed being impervious.
6. FWTR is the fraction of the watershed covered with water surface.
7. FFOR is the fraction of the watershed being forest.
8. VINTMR is the maximum depth of precipitation interception (in).
9. FFSI is the fraction of the snow falling on the forest area that is intercepted. This is assumed to be lost directly to evaporation, without ever reaching the snow on the ground.
10. SPBFLW is the snowpack basic maximum fraction in liquid water. It is an index to the amount of water which will be held in the snowpack before water produced at the surface is able to drain toward the bottom of the snowpack. Very little data are available on the magnitude of this parameter and its variation with snow density. Studies by Anderson and Crawford (1964) show a range for SPBFLW from 4 to 6 per cent of the water equivalent of the snowpack.

11. SPTWCC is the snowpack minimum total water equivalent for maximum basin coverage (in). In the model it is assumed that when the water equivalent of the current snowpack is less than SPTWCC the ratio of actual melt to 100 per cent cover melt is directly proportional to the ratio of the current snowpack water equivalent to SPTWCC.

12. DSMGH is the rate of daily snowmelt from ground heat. The model assumes a constant DSMGH. In areas with shallow snowpacks and long cold periods DSMGH would be zero. Otherwise, Anderson and Crawford (1964) suggest a value of 0.01 or 0.02 inches.

13. PXCSA is the precipitation index for changing the snow albedo. In the model a snow albedo index (SAX) is set to vary from zero to fifteen, with zero signifying maximum albedo and 15 a well aged snow surface. The value of SAX is decreased by one whenever new snowfall accumulation reaches PXCSA and increased by one whenever snow accumulation is down to PXCSA/2 or each day to account for snow aging.

14. MRNSM is the maximum rate of negative snowmelt (in). This is an index to the cold content and the extent of liquid water content refreezing of the snowpack. It is used to estimate the amount of negative melt as based on some empirical relationships developed by Anderson and Crawford (1964).

15. SPM is the snow precipitation multiplier. It corrects for gage catch deficiencies that may exist when precipitation is in the form of snow. Such deficiencies may be as high as 60 per cent for winds of 35 miles per hour (Linsley, et al. 1958). Based upon prevailing wind conditions, this
parameter may be estimated. It can also be
determined by comparing synthesized and observed
snowmelt runoffs.

16. RMPF is not a parameter but an output option which
is read together with some of the watershed
parameters. It is the requested minimum daily peak
flow to be printed. Instantaneous streamflow due
to direct runoff must reach its value sometime
during the day before the 24 hourly flows for that
day are printed.

17. RGPMB is the ratio of the average rainfall over
the basin to the average rainfall at the base gage.

18. GWETF is the groundwater evapotranspiration factor.
This estimates the current rates at which swamp
vegetation and deep rooted plants are drawing water
from that below the water table. Its value is
usually zero and where it is not it may be estimated
by trial and error.

19. SUBWF is the amount of water entering or leaving
the basin through subsurface flow not measured by
the stream gages. For most basins this parameter
is zero and where it is not it could be estimated
by trial and error.

20. OFMN is the Manning's roughness coefficient for
overland flow on the flow plane.

21. OFMNIS is the Manning's roughness coefficient for
overland flow over impervious surfaces. Estimates
of the above roughness coefficients are given by
Crawford and Linsley (1966) and Chow (1959).

22. OFSS is the average slope in feet per foot of the
overland flow surfaces perpendicular to the receiving
channel. This may be estimated from spot measure-
ments or by using a topographic map of the watershed.

23. OFSL is the overland flow slope length. It indi-
cates the average distance that surface runoff
must travel before reaching a channel.

24. CHCAP is a measure of the channel capacity. Its
value is used to distinguish between flood flow
and contained flow so that the channel storage
routing index may be changed accordingly. It may be estimated from a profile analysis of the channel system. It may also be estimated as the "base" used by the U.S. Geological Survey in determining which flood peaks to list in their Surface Water Records.

25. CTRI is an array of the channel time-delay histogram. The elements of the time-delay histogram may be found by estimating the time of concentration of the watershed, the horizontal length and the slope in feet per foot of the channel. The horizontal length is the measured distance from the most remote point to the outlet of the basin. The difference in elevation between these points divided by the length yields an estimate of the average slope. The time of concentration divided by the length gives the average velocity of flow of the water in the channel. When multiplied by the time routing increment this average velocity yields the stream distance for separating isochrones on a map of the watershed. The area bounded by each pair of isochrones is planimetered, and the fraction of the watershed contained between each pair is estimated. The time-area histogram is a tabulation of these fractions, proceeding in an upstream direction.

The second type of watershed parameters include the following:

1. BUZC is the upper zone nominal storage level (in). Its magnitude is quite small compared to the lower zone storage capacity.

2. LZC is the nominal storage level that represents the median value of lower zone moisture storage (inches). It is roughly equal to 1.2 times the water holding capacity of the lower zone.

3. BMTR is a measure of the basic maximum infiltration rate (BMIR). It is used in estimating the value of BMIR and, hence, CMIR. These first three parameters LZC, BUZC, and BMIR are interrelated. They may be estimated by trial and error or by examining the physical effects of storage and infiltration rate interactions as each parameter is physically defined.
4. SUZC is an index for the upper zone storage adjustment. Its purpose is to adjust BUZC in order to account for seasonal changes in its value as a result of the effects of vegetation and cultivation practices.

5. GFIE is an index of the effect of ground freezing on the infiltration capacity of the soil. It may be used to drastically reduce the infiltration capacity during the winter months when the soil surface is frozen.

6. SIAC is a seasonal infiltration adjustment constant. Its purpose is to modify BMIR to take into account the effect of vegetation and cultivation practices.

7. ETLF is an index used to estimate the maximum rate of evapotranspiration. The maximum rate is estimated as the product of ETLF and the ratio LZS/LZC. This maximum rate is used to estimate the current actual evapotranspiration in a manner shown on Figure 9. Crawford and Linsley (1966) recommend ETLF values ranging from 0.20 to 0.30 inches depending on the watershed cover.

8. BIVF is the basic interflow volume parameter. It is used to define the variable CIVM in Figure 8. It controls the shape of the hydrographs by regulating the amount of moisture entering interflow. Increasing BIVF will increase CIVM thus, reducing the storm peaks and extending the hydrographs' recession limbs.

9. BFRC is the base flow recession constant.

10. BFNLR is a base flow nonlinear recession index. It is used to provide a curvilinear base flow recession. Its value is normally between 0.90 and 1.0. When it is equal to 1.0, the model will use a linear base flow recession.

11. IFRC is the interflow recession constant. Its value as well as those of BFRC and BFNLR may be estimated by trial and error. They may also be found by graphical or mathematical analysis of hydrographs.
Evapotranspiration does not occur since energy is limiting

Current rate from climatological data

Evapotranspiration does not occur since moisture is limiting

Actual evapotranspiration

Maximum rate = ETLF x LZS/LZC

Percent of the watershed with daily evapotranspiration opportunity equal to or less than the indicated value.

Figure 9. Cumulative frequency distribution of actual evapotranspiration over a watershed (Crawford and Linsley, 1966)
12. CSRX is a streamflow routing index used to account for channel storage when flows are less than one-half the channel capacity (CHCAP). To simulate channel attenuation or storage, the outflow hydrographs produced by channel translation (using the time-area histogram) are routed through a hypothetical storage system or reservoir. The routing equation used in the model is

\[ O_2 = \bar{I} - CSRX(\bar{I} - O_1) \]

where \( O_2 \) is the reservoir outflow at the end of the selected time interval, \( O_1 \) is the outflow at the beginning of the interval, and \( \bar{I} \) is the average inflow during the time interval.

13. FSRX is a streamflow routing parameter used to account for channel as well as flood plain storage when streamflows are greater than twice the channel capacity. Under such flow condition FSRX is substituted for CSRX in the routing equation. When the flow is between one-half and twice CHCAP, the model interpolates between CSRX and FSRX. When the average inflow \( \bar{I} \) in the routing equation is zero, the channel routing parameter becomes a recession constant for the water in channel storage. The values of CSRX and FSRX may then be estimated by analyzing the observed hydrographs.

14. EXQPV is an exponent which is used to vary the velocity with flow rate. It is used only when option 13 is in effect. The time routing of the storm hydrograph is made nonlinear by making the flow velocity proportional to the flow rate raised to the exponent EXQPV. Ross (1970) recommends a value of about 0.25 for EXQPV.

Input data indicating relevant dates

1. NDTUZ is the approximate date of the year in which the thawing of the upper soil surface begins. In Iowa this usually occurs during the first or second week of March. In the model it is assumed that from day one (January first) through NDTUZ the soil surface is frozen thus reducing infiltration drastically. During this period the basic maximum infiltration rate index, BMTR, is divided by the parameter GFE in order to obtain the basic maximum infiltration rate, BMIR. Otherwise, BMIR is set equal to BMTR.
2. NDIM is the last day in which pan evaporation measurements are taken. After this date the measurements are stopped for the duration of the winter season. This day usually falls in the second or third week of November in Iowa.

3. NDFM is the day (going from 1 to 365 or 366) in which pan evaporation measurements are re-started after being temporarily stopped during the winter months. In Iowa this usually falls in the first week of April.

**Climatological data**

Hourly precipitation and daily potential evapotranspiration are the major climatological data required by the model. In addition to these, the snow-melt subroutine requires solar radiation, snow potential evaporation, snow albedo, and daily maximum and minimum temperature data.

**Hourly rainfalls**

Hourly rainfalls should be obtained from recording rain gages best representing the watershed. The Environmental Data Services, National Oceanic and Atmospheric Administration of the U.S. Department of Commerce compiles and publishes hourly precipitation records from recording rain gages scattered all over the United States. On rare occasions, records from locally maintained recording rain gages are also available.

In the event that two or more recording rain gages represent the storm patterns within the watershed, the average hourly rainfall may be estimated by using any of the areal rainfall averaging techniques such as the arithmetic
mean, Thiessen, and isohyetal methods.

Daily rainfall from storage rain gages should also be obtained where they can be averaged with the recording rain gage totals. The model is set up to read and average data from one recording and one storage gage only. When more than one of each type of rain gage are to be used, the model must be modified or the averaging for each gage type must be done first before the final averaging of the recording and storage gages averages. Another alternative is to modify the model structure so as to provide the option of subdividing a watershed into segments and modeling runoff as the sum of the segment totals. Watershed segmentation is one aspect of the Stanford Watershed Model that does not exist in the Kentucky Watershed Model.

The averaging of the storage gage totals with the recording gage totals may be accomplished by determining the fraction of the total watershed area represented by the storage gages. This fraction serves as the storage gages weighting factor (WSG). The daily rainfall in the watershed is computed as the sum of WSG times the storage gage total plus (1 - WSG) times the recording gage total. The hourly rainfalls are then multiplied by the ratio of the daily rainfall average and recording gage daily total to obtain the average hourly rainfalls within the watershed.

Problems may arise in comparing the storage gage daily
rainfalls with those of the recording gage daily totals as a result of the differences in times over which these daily measurements were obtained. To correct this, the model requires the storage gage reading time, SGRT. This is the integer value on the 24-hour clock corresponding to the hour closest to the reported reading time. In the event that a storage gage is relocated, an option is available for reading new SGRT and WSG values (SGRT2 and WSG2).

Potential evapotranspiration The model uses pan evaporation to estimate the actual evapotranspiration losses from the watershed. The model assumes that the evapotranspiration losses occur from the upper zone first, and in the event that all the upper zone moisture has evapotranspired, from soil moisture storage (LZS). Daily pan evaporation measurements are used at times when such measurements are available. During the rest of the water year when such measurements are discontinued, the pan evaporations are estimated by the model.

To estimate actual evapotranspiration losses, existing local data showing the ratios of actual evapotranspiration to pan evaporation at various times of the year are used. These ratios are not included in the input data but are incorporated in the model structure. If the model is to be used in places other than Iowa a slight modification of these ratios might be desirable.

An option is included in the model to read average pan
evaporation values over fixed ten-day periods. These periods may be determined by reading the listing given in Appendix A. They are also specified by Ross (1970). This option is used only when the closest evaporation pan is too far away for daily fluctuations in evaporation to be representative of the conditions over the watershed. Another option in the KWM as listed by Liou (1970) is to use only an estimate of the potential annual lake evaporation. This option is used only when the first two options cannot be exercised. The KWM uses a subroutine to subdivide the annual lake evaporation average over the days of the year. This option and, hence, the subroutine is not included in the model listed in Appendix A in order to save computer compilation time. It is, however, discussed by Ross (1970) and listed by Liou (1970).

**Solar radiation** Hourly solar radiations incident on the watershed are used in the synthesis of streamflow due to snowmelt. Such data are difficult to obtain as only daily totals at very few stations are published by the Environmental Data Services, National Oceanic and Atmospheric Administration of the U.S. Weather Bureau. This is one of the reasons why the snowmelt subroutine of the SWM has not been widely used even in areas where there is significant snowfall.

The Stanford Watershed Model described by Anderson and Crawford (1964) uses daily net solar radiation from which hourly values were calculated by means of a relationship
expressing hourly radiation as a percentage of the total. This relationship is missing in the KWM snowmelt subroutine.

The snowmelt subroutine listed in Appendix A is similar to that listed by Liou (1970) except for a few modifications. The subroutine assumes a fixed 10-hour day for the duration of the snowmelt season. It further assumes an equal distribution of the daily radiation total among the 10 hours of the day. The input data are, therefore, the hourly solar radiation values which in effect are the daily totals divided by ten. The model requires input data only for the months of November, December, and from January through April of each water year. For the rest of the water year when there is usually no snowfall, a fixed value is assumed. Such value has no effect on the operation of the model.

In the program listing on Appendix A, the day 366 corresponds to the 29th day of February of each leap year. When the current water year does not contain such a day, its value will not be used and, hence, any convenient value may be used. This is also true for the other snowmelt input data such as daily minimum and maximum temperatures.

The assumption of equal hourly distribution of solar radiation within a day is not valid where accurate reproduction of hourly snowmelt is needed. Given the scarcity of solar radiation data coupled with the hourly fluctuations in incident net radiation from one watershed to another as a
result of atmospheric interference, this assumption offers a great deal of simplification without further loss of accuracy in daily or monthly snowmelt totals.

**Snow albedo** The model uses fifteen estimates for the fraction of the incoming solar radiation reflected by the snow surface depending on the value of the snow albedo index, SAX. A clean dry snow surface will probably reflect about 80 per cent of the incident short-wave radiation. As the snow ages, its albedo may drop to as low as 50 per cent. The 15 snow albedo estimates (FIRR) will normally be within this range.

**Temperature** Representative daily minimum and maximum air temperatures are required for the months in which incident hourly radiation values are also required. For the rest of the water year (May through October), it is assumed that no snowfall occurs or that if some snowfall does occur, it does not stay long on the ground.

The model assumes the daily minimum and maximum temperatures occur at 4 (4 a.m.) and 16 (4 p.m.) hours of the day, respectively. After correcting for lapse rates, the model calculates hourly values by fitting a sine curve to the two temperature extremes. The points of inflection of such a curve are at 10 and 22 hours of the day.
Snow evaporation  The model reads average potential snow evaporation for fixed 10-day periods and, hence, only 37 input values are required. Snow evaporation values may be estimated with reasonable accuracy. They are close to zero even during periods of heavy snow accumulation and zero otherwise. Since they are relatively small, errors in their estimate will not significantly affect the water balance of a watershed.

Initial moisture conditions  The streamflow synthesis begins on October first which is the first day of any water year. For the first water year to be run, estimates of the initial moisture storages in interflow (IFS), the upper zone (UZS), the lower zone (LZS), and groundwater (GWS) must be supplied. In addition, an initial estimate of the base flow nonlinear recession index (BFNX) is also needed. Ross (1970) suggests a value of BFNX equal to GWS for a starter. Unless a large storm occurred within the last few days prior to October first, IFS and UZS will be zero. The lower zone (UZS) and groundwater (GWS) storages may be estimated by studying the water balance within the watershed for the entire or the latter part of the previous month (September). These may also be reasonably estimated by trial and error. It will normally take three or four computer runs before reasonable estimates are obtained. All of these initial moisture storages are expressed in average inches of moisture throughout the
drainage area.

Other input data include the daily average streamflows and flow diversions in and out of the watershed in cubic feet per second. The daily recorded streamflows are optional inputs to the KWM but are required by the superimposed erosion model. Daily suspended sediment loads in tons are optional inputs to the erosion model and are used only for comparison with synthesized sediment loads.

Parameters Optimization

The long list of parameters required by the watershed model is an indication of the degree of difficulty new users encounter in attempting to use the model. Although most of these parameters can be readily found from hydrologic or meteorologic records and topographic maps, there are those that are not easily derived. The only way to estimate these parameters, apparently, is to relate them empirically to measurable watershed characteristics. This can only be achieved through the extensive use of the model hoping these parameters such as the basic maximum infiltration rate and seasonal infiltration adjustment constant can be consistently derived by different investigators. This appears plausible but, at present, the effort has barely started.

The Stanford group, being the first to develop a comprehensive watershed model, has also pioneered the search for
parameter optimization techniques. Through parameter interactions and sensitivity studies, they were able to offer some guidelines and estimates which are invaluable to potential model users. Yet, the trial and error approach to estimating some of the more elusive parameters is still much a part of these guidelines. Such a calibration process is not only time consuming but also highly subjective. Different investigators may come up with substantially different sets of parameter values for the same data.

A pioneering effort at eliminating this trial and error approach has been made by James (1970) and Liou (1970). They developed a computerized procedure for selecting the optimum set of parameter values for the KWM in a consistent and objective manner. The self-calibrating version of the KWM (also called OPSET) which utilizes this procedure optimizes the selection of 13 watershed parameters. This self-calibrating model was tested on numerous small watersheds in Kentucky.

Considering the magnitude of the task, the results of the tests using OPSET are of course inconclusive and incomplete. Also, OPSET does not take into account snowmelt and, hence, is not applicable where appreciable runoff comes from snowmelt. Nevertheless, such an approach yields rough estimates of some parameters and appears to give promise of eventual success if sufficient effort were devoted toward its
expansion (to include snowmelt among other things) and modifi-
cation.

Appendix C lists some typical input data for the watershed model listed on Appendix A. The list also includes the input data required by the superimposed erosion model. The input data are for the Four Mile Creek watershed near Traer, Iowa. The values of the watershed parameters on the listing were estimated using OPSET as well as the guidelines given by Anderson and Crawford (1964) and Crawford and Linsley (1966).
CHAPTER IV. SHEET EROSION MODEL

Development of the Sheet Erosion Model

It was not until just recently that attempts have been made to study the physical phenomena involved in the soil erosion process. Although the mechanisms involved in the process have not changed and man's involvement in the problem of soil erosion dates back to the earliest recorded civilization, the fundamental mechanisms involved in the process are not yet fully understood. This may be partly due to the availability of practices and methods of coping with the problem. These methods have been developed by trial and error.

In spite of the availability of erosion control practices, the general field of soil erosion is of utmost importance for a variety of reasons. With the growing population and limited resources, modern society is undergoing a reordering of priorities. The control of streams, protection of the environment, roads, and hydraulic structures as well as the preservation of the landscape become necessary and feasible for modern society. There is an ever present need for the sound prediction of sheet and rill erosion from agricultural as well as urban watersheds.

It was pointed out in Chapter II that several empirical equations for predicting sheet and rill erosion have been proposed. These equations have been developed by correlating
observed erosion rates from small experimental plots with the multitude of variables existing in these plots. As pointed out by James (1970), such equations have glaring weaknesses such as:

1. They are not comprehensive. The many possible variations in climate and watershed conditions are so great that it is impossible to develop a comprehensive correlation covering all types and gradations in variations. As a result, errors of the magnitude of 300 to 400 per cent are not uncommon with the use of such equations (Beer et al., 1966).

2. They are usually applicable on a yearly basis or longer. When assessed against the need for predicting instantaneous sediment loads in streams (i.e., fish and wildlife protection), such equations are of very little use.

3. They do not take advantage of the physical processes occurring within the watershed. Without the use of such information it is impossible to use them on large watershed complexes undergoing some modifications.

The above discussions point to the need for a sound physical model of the soil erosion process. It was pointed out in Chapter II that several mathematical models designed to serve as frameworks for quantitative soil erosion models have been proposed. Their possible applications are, however, hindered by the lack of reliable information on the overland flow components of the measured total river discharges.

The development of the digital watershed models that distinguish between the flow components which make up the total river discharge opens a new horizon in soil erosion
research. Negev's (1967) exploratory study shows that an erosion model based on the analysis of the processes involved and currently available information shows eventual promise if sufficient efforts are directed toward this objective.

The major elements of the sheet and rill erosion model are shown on Figure 10. The model does not differentiate between sheet and rill erosion since there is no clearcut distinction between the two forms of erosion. Hence, they will be referred to as simply sheet erosion.

Precipitation, overland flows, and daily recorded streamflows are the major input data required. The overland flows are synthesized by the watershed model upon which the erosion model is superimposed. Daily recorded streamflows are used instead of the synthesized flows in order to minimize errors in estimating channel banks and bed scouring.

The erosion model computations begin with the first occurrence of rain or snowmelt. In the case of rain, the raindrops hitting the ground splash soil particles in all directions. The quantity of soil splashed will depend upon the impact force, watershed cover, land slope, wind direction, rainfall characteristics, and the depth of the water layer above the soil surface.

The water layer above the soil surface serves as a buffer zone against the impact of the raindrops. It is, therefore,
Figure 10. Flowchart of the sheet erosion model superimposed on the watershed model
reasonable to assume that the impact force decreases with the water depth. Similarly, the impact force decreases with the slope of the soil surface since the component force normal to the surface is a function of the cosine of the slope. Denser vegetal cover also reduces the impact force of the raindrops.

The individual influences of the above factors on the amount of soil splash are not well understood. At very low water depth, the buffering effect of the water film is offset by its lubricating effect on the individual soil particles. As the depth increases, this buffering effect becomes more pronounced. The effects of wind speed and land slope are similar in the sense that they both tend to decrease the component of the impact force normal to the surface. It must be noted, however, that while land slope tends to reduce the impact force it has an overall tendency to increase the erosion rates as a result of greater overland flow rates and soil splash transport downslope.

Numerous experimental studies have been conducted on splash erosion. Since under normal field conditions neither the drop velocity nor the drop diameter can be conveniently measured, most of these investigations were directed toward finding functional relationships among splash erosion, rainfall intensity, and kinetic energy. In a recent study Bubenzer and Jones (1970) estimated the quantity of soil
splash from small plots by the following expression

\[ \text{SPLASH} = A \ (\text{KE})^n \ I^m \]  \hspace{1cm} (4-1)

where

\begin{align*}
\text{SPLASH} &= \text{amount of soil splash} \\
\text{KE} &= \text{kinetic energy of the raindrops} \\
I &= \text{rainfall intensity} \\
A &= \text{constant} \\
n, m &= \text{exponents having ranges of 0.27 to 0.55 and 0.83 to 1.49, respectively}
\end{align*}

The kinetic energy of rain is estimated by Mihara (1951) as

\[ \text{KE} = B \ I^{1.20} \]  \hspace{1cm} (4-2)

where \(B\) is a soil constant. Combining Equations (4-1) and (4-2) gives

\[ \text{SPLASH} = A \ B \ I^{m + 1.2n} \]  \hspace{1cm} (4-3)

Bubenzer and Jones (1970) tabulated their experimental values of \(m\) and \(n\) for different soils. Their analysis shows mean values for all soils studied of 0.42 and 1.29 for \(m\) and \(n\), respectively. Substituting these values in Equation (4-3) gives

\[ \text{SPLASH} = A \ B \ I^{1.61} \]  \hspace{1cm} (4-4)
where ALPl is approximately equal to two. It is interesting to note that this is the same relationship Meyer and Wischmeier (1969) obtained after carefully reviewing earlier research findings. In a recent study, Holy and Vitkova (1970) derived a relationship similar to Equation (4-3). Their study shows that the exponent \((m + 1.2n)\) is a function of the land slope.

From the above considerations of the factors affecting the amount of soil splash it appears that the amount of soil splash for any given time interval may be expressed by the following equation

\[
\text{SPLASH} = \text{SC}_P \cdot \text{LSP} \cdot I^{\text{ALPl}} \cdot \exp(-k \cdot \text{SPDR})
\]  

(4-5)

where

- \(\text{SC}_P\) = soil and soil cover factor
- \(\text{LSP}\) = land slope factor
- \(k\) = exponent greater than one
- \(\text{SPDR}\) = the overland flow depth

On a flat surface the net transport of soil particles by raindrop impact will be zero. Otherwise, a portion of the soil splashed will be transported downslope. Ekern (1951) found that the net amount of soil transported downslope is directly proportional to the land slope. This amount is transported for a certain distance only and in the absence of
overland flow to transport it further downslope only the particles splashed near the rills and waterways will find their ways into the streams. This amount of soil splashed directly into the waterways may be estimated as

$$SSPL = AR_d \times OFSS \times SPLASH$$

where

$$OFSS = \text{average overland flow surface slope}$$

$$AR_d = \text{area representing the total land surface within a splashing distance to a stream surface}$$

$$SSPL = \text{the amount of soil splashed directly into the stream surfaces for any given time interval}$$

By definition, detachment by rainfall is always greater than soil splash. The mechanisms involved in both processes are, however, the same. An expression of the amount of soil detached by rainfall may thus be obtained by multiplying the right hand side of Equation (4-5) by a constant. Such an expression is needed in estimating the amount of detachment storage at any given time.

The detached material that does not directly fall on a stream surface may be redeposited on the ground, on plant leaves and residues, or may remain in suspension and be transported downslope in case overland flow does occur. The relatively finer particles in suspension will find their ways into the streams while the coarser ones may be deposited at some points along the overland flow surface. The redeposited
soil particles will be left loosely on the ground for some time as detachment storage. Upon the occurrence of the next overland flow, they may be picked up and added to the soil that is already being transported.

The detached particles in storage will eventually form aggregates with the shrinkage of the soil mass and the cementation of the clay particles and will no longer be available for overland flow pickup if left too long on the ground. The rate at which these loose particles form aggregates or the rate at which the detachment storage decreases with time will depend on the soil properties, moisture content, and climatic conditions. Higher values of soil aggregate formation may be expected during the spring and summer months when evapotranspiration rates are high. The rate at which the total detachment storage decreases can be approximated by the decay type function

\[ TSST = TSST_0 / \exp(\text{PWER} \text{ Time}) \]  \hspace{1cm} (4-7)

where

\[ TSST_0 \] = total detachment storage at the beginning of the time interval

\[ TSST \] = total detachment storage at the end of the time interval

\[ \text{PWER} \] = ALP4/ALP5

\[ \text{ALP4} \] = soil factor

\[ \text{ALP5} \] = climate factor
Time = time interval

Soil detachment by rainfall may be controlled by vegetal cover, mulching, and cultivation practices. In addition, the amount of loose soil particles in storage may be drastically increased by alternate thawing and freezing, plowing, and earth moving operations. The influences of these factors are extremely difficult to evaluate quantitatively. Some of these are, however, more pronounced during the spring months while the canopy interception effects progressively increase as the growing season progresses. The effect of canopy cover may be approximated through the use of some crop growth indices such as the leaf area or the water use index.

A certain amount of scouring may also occur with overland flow. This will depend mostly on the stresses generated by the overland flow on the soil surface. The average shear stress on an overland flow plane may be approximated by

\[ \tau_o = \gamma \cdot SPDR \cdot OFSS \]  

where

- \( \tau_o \) = average shear stress on the overland flow plane
- \( \gamma \) = specific weight of water
- \( SPDR \) = depth of overland flow for the specific period
- \( OFSS \) = overland flow surface slope
Equation (4-8) though valid only for small slopes \((\sin\theta = \theta)\) gives stresses within the order of magnitude of those for greater slopes. On ideal conditions where overland flows occur as thin film flows over a uniformly smooth surface, the shear stresses associated with such flows even for very steep slopes are usually very small compared to the shear strength of cohesive soils. Under such conditions, only a very small amount of soil will be detached by overland flow and, hence, may be considered as negligible.

Overland flow under normal field conditions is usually concentrated along well defined paths or rills. Under such conditions, soil detachment by overland flow may be significant and may be estimated by the expression

\[
SCROV = BETA5 \ SPDR^{BETA6} \tag{4-9}
\]

where

- \(SCROV\) = amount of overland flow scour
- \(BETA6\) = an exponent
- \(BETA5\) = a constant representing the soil characteristics and the overland flow surface slope

The exponent \(BETA6\) will be greater than or equal to one. Its value is equal to one under the idealized condition of flow of thin films. Where flow is concentrated along well defined rills such that the actual flow depth is greater than the average overland flow depth, \(SPDR\), its value will be greater than one.
The ability of overland flow to transport the detached soil particles depends on the flow depth, flow velocity, and the land surface and soil characteristics. The overland flow velocity may be related to OFSS and SPDR by the following power function

\[ \text{VELOVQ} = S_c \text{ SPDR}^{\lambda_1} \text{ OFSS}^{\lambda_2} \]  

(4-10)

where

- \( \text{VELOVQ} \) = average velocity of overland flow
- \( S_c \) = soil constant
- \( \lambda_1, \lambda_2 \) = exponents with values less than one.

Equation (4-10) is based on a well known equation (Manning's Equation) which is widely used in estimating the average velocity under turbulent flow conditions. Overland flow may well occur under both turbulent and laminar flow conditions. On the assumption that Equation (4-10) is valid, the transport capacity of overland flow may be expressed as

\[ \text{TROVQ} = \text{SL}_F \text{ OFSS}^\delta \text{SPDR}^{\text{ALP2}} \]

or simplifying the above expression further

\[ \text{TROVQ} = \text{BETA3 SPDR}^{\text{ALP2}} \]  

(4-11)

where
TROVQ = overland flow transport capacity

SL_F = soil and surface roughness factor

δ = an exponent

ALP2 = a constant

BETA3 = SL_F OFSS^δ

Using Laursen's (1958) findings that the sediment carrying capacity of flowing water is approximately proportional to the fifth power of the flow velocity, VELOVQ, and Equation (4-10), Meyer and Wischmeier (1969) suggested that the exponents ALP2 and δ are both approximately equal to 1.67.

Equation (4-11) is a potential transport function and as such should be greater than or equal to the actual overland flow transport rate, ATROVQ. Thus the actual transport rate from storage is equal to TROVQ when TROVQ is less than TSST. Otherwise, TROVQ is equal to TSST.

Under normal field conditions, Equation (4-11) applies only to the unripped sections of a watershed where the overland flow transport capacity is usually the limiting factor to sediment movement. This equation uses average values for overland flow depth, SPDR, and land slope OFSS which are representative of the flow conditions in the unripped areas of the watershed since these areas represent a very large fraction of the total watershed area.
Overland flow scouring usually occurs in significant amount only in the rilled areas of the watershed where flow converges on steeper overland flow slopes. The combination of these two factors results in greatly increased transport capacity which is not reflected in Equation (4-11). Under such condition, the overland flow transport capacity is not a limiting factor to sediment movement. Hence, the overland flow scouring phenomenon as expressed by Equation (4-9) is treated independently of Equation (4-11).

The amount of soil particles picked up from impervious areas will be influenced by the same factors affecting soil splash. Since this amount constitutes only a small portion of the total sheet erosion from agricultural watersheds, it may be conveniently approximated as

\[ \text{IMPU} = KP \times \text{FIMP} \times \text{SPLASH} \]  

(4-12)

where

- \( \text{IMPU} \) = amount of sediments picked up from impervious areas
- \( KP \) = empirical constant
- \( \text{FIMP} \) = fraction of the watershed being impervious

Upon entering the waterways, the finer particles may remain in suspension and be transported downstream. The coarser particles may be deposited, roll, or bounce along the bed. Along with the deposition of the eroded particles, channel bed and bank scouring may simultaneously be occurring. Factors
affecting the equilibrium quantities between deposition and scouring are the fall velocities of the particles and the transporting and scouring abilities of the streamflow.

The mechanics of sediment transport by streams are not well understood. There are no reliable theories concerning the suspended or bed load discharges of streams and the currently available equations are largely empirical in nature. Progress is being made, however, on the mechanics of sediment suspension and this phase of the problem is relatively well understood. This progress is greatly enhanced by the development of the modern concepts of turbulent flow. Unfortunately, however, theoretical considerations while being confirmed in small laboratory flume experiments, do not check very well with the actual stream data. Furthermore, the application of these theoretical equations requires the estimation of certain parameters which are not normally known (Raudkivi, 1967; Vanoni et al., 1960).

For small agricultural watersheds where gully and larger rill erosion contributions are relatively small, it could be reasonably assumed that most of the eroded soil particles are relatively finer and will remain in suspension and, hence, will be transported as wash load. This implies that the eroded soil particles will move through the system in single runoff event. This assumption may not be valid where there are drastic changes in the slope, soil shear stresses, or overland flow surface roughness. Under such conditions, deposi-
tion usually occurs at the base of the slopes where the shear stresses and flow resistance change.

The scouring of the channel banks and bottom may contribute to the sediment load significantly especially in case of larger floods. This contribution to the total suspended sediment load is difficult to estimate. A portion of sediment scoured from bed and banks of channels may occur alternately as bed load or interload. A review of the better known bed load and interload formulas showed that errors involved of magnitudes of 100 per cent or more are to be expected from their uses and that it is not possible to recommend any formula or formulas (Vanoni et al., 1960).

In view of the imperfect state of the theories of sediment transportation, the estimation of the portion of the sediment load coming from channel banks and bed scouring must rely on an empirical approach. A practical objective then is to obtain an empirical equation in terms of the relevant hydraulic parameters and sediment properties. Such equation may be of the form

\[ \text{SCOUR} = f(Y,V,ds,n,S,\gamma d) \]

where

- \text{SCOUR} = channel bed and bank scouring
- \( Y \) = flow depth in channel
- \( S \) = channel grade
- \( V \) = average velocity of flow
n = channel roughness coefficient
\( ds \) = mean sediment diameter
\( \gamma_d \) = specific weight of sediments

For a given stream, \( Y, V, \) and \( S \) are related to the discharge, \( DRSF \). The remaining parameters, for simplicity, may be represented by a single parameter, \( BETA4 \). Thus

\[
SCOUR = BETA4 \ DRSF^{ALP3}
\]

(4-13)

where \( ALP3 \) is an exponent. In the above equation \( DRSF \) is the mean daily discharge and, hence, the equation applies on a daily basis only.

For a specific period, the total amount of sheet erosion is the sum of the various sheet erosion components. This total amount is given by

\[
USFA = ATROVQ + SCROV + SSPL + IMPU
\]

(4-14)

where

\[
USFA = \text{total sheet erosion rate for the specific period}
\]

\[
ATROVQ = \begin{cases} 
TROVQ; & TROVQ \leq TSST \\
TSST; & TROVQ > TSST 
\end{cases}
\]

and the rest of the terms are as previously defined. Substituting Equations (4-5), (4-6), and (4-12) into Equation (4-14) yields

\[
USFA = ATROVQ + SCROV + (AR_d \ OFSS + KP \ FIMP) \ SC_F \ LS_F \times \exp(-k \ SPDR) \ I^{ALP1}
\]
or simplifying further

\[ USFA = ATROVQ + SCROV + SSPLH \] (4-15a)

where

\[ SSPLH = BETA_1 \cdot SPIX \]

\[ BETA_1 = (AR_d \cdot OFSS + KP \cdot FIMP) \cdot SC_F \cdot LS_F \cdot \exp(-k \cdot SPDR) \] (4-15b)

\[ SPIX = I^{ALP1} \]

In the model a single parameter, \( BETA_1 \), is used to represent the combined effect of the different watershed variables used in deriving Equation (4-15b). The use of single parameter to represent these variables may be justified by the fact that the sheet erosion components \( SSPL \) and \( IMPU \) usually represent only a small portion of the total sheet erosion, \( USFA \). Also, under field conditions the effect of the depth of overland flow on the raindrops impact is usually small except in areas where there are numerous shallow depressions. Furthermore, in view of the fact that the average overland flow slope for the entire watershed cannot be accurately estimated, the effect of \( OFSS \) cannot be properly evaluated unless several watersheds with sharply contrasting \( OFSS \) values are modeled. Such a job requires a great deal of effort and computer time.

The daily synthesized suspended sediment load is computed as

\[ TDSSL = SCOUR + DSSE \] (4-16)
where

TDSSL = total daily synthesized suspended sediment load

DSSE = summation of USFA over the 24-hour period

Operation of the Sheet Erosion Model

Figure 11 shows the schematic diagram of the proposed sheet erosion model as based on Equations (4-15a) and (4-16). A simplified loose soil particles accounting procedure is used by the model. First, the soil splash index is calculated for the specific period. This index is then used to estimate the soil detachment storage, SST0, for the same period using the expression

\[ SST0 = BETA2 \times REDX \times SPIX \]  \hspace{1cm} (4-17)

where

\[ BETA2 = \text{a watershed constant} \]

\[ REDX = \text{an index to the reduction in rainfall energy as a result of the changes in the vegetal cover and the form of precipitation.} \]

When the precipitation is in the form of rain, REDX is approximated by a vegetation water use index. If the soil is bare, REDX is set equal to one. During the crop growing season, it is reduced in proportion to ratio of the current potential water use of the vegetation to the maximum potential water use at the peak of the vegetal growth. When precipitation is in the form of snow, REDX is set equal to zero.
Figure 11. Schematic diagram of the proposed sheet erosion model
The estimated soil detachment storage, SST0, is added to the loose particles in storage at the beginning of the period to obtain the current value of TSST. Accretions to TSST due to sources other than rainfall detachment are also added to TSST on the approximate day they occurred. The total soil particles storage is in turn continuously being depleted by overland flow transportation and soil aggregates formation.

The program listing for the sheet erosion model is given in Appendix A. This program which includes both the watershed and the sheet erosion models has been run on an IBM 360/65 computer. For a year of data the computer execution time is about 35 seconds.

Inputs and outputs The input data required by the sheet erosion model include the following:

1. Mean daily recorded streamflows. These are used to estimate the daily amounts of suspended sediments coming from channel banks and bed scouring. The principal sources of information for these data are the U.S. Geological Survey Surface Water Records.

2. Daily recorded suspended sediment loads. These are needed for statistical comparisons with the synthesized values. When such comparison are not required or such information are not available, an option is available for excluding them from the analysis. The usual sources of information on suspended sediment loads are the U.S. Geological Survey Water Quality Records.
3. A group of constants representing watershed parameters.

4. Hourly rainfalls and hourly or quarter-hourly overland flows.

The hourly rainfalls are also required by the watershed model in order to synthesize the overland flows.

The output from the model consists of the daily printouts of the computed sheet erosion, channel scouring, and suspended sediment loads. An option is also available to print out the recorded suspended sediment loads. A sample of inputs to the program is given in Appendix C. A summary of the various input and output variables is given in Table 1.
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<td>Average daily recorded streamflows</td>
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<tr>
<td>DRSL</td>
<td>R</td>
<td>366</td>
<td>tons</td>
<td>Daily recorded suspended sediment loads</td>
</tr>
<tr>
<td>DRHP</td>
<td>R</td>
<td>366,24</td>
<td>inches</td>
<td>Dated recorded hourly precipitation</td>
</tr>
<tr>
<td>ALP1</td>
<td>R</td>
<td>1</td>
<td>-</td>
<td>See Equation (4-4)</td>
</tr>
<tr>
<td>ALP2</td>
<td>R</td>
<td>1</td>
<td>-</td>
<td>See Equation (4-11)</td>
</tr>
<tr>
<td>ALP3</td>
<td>R</td>
<td>1</td>
<td>-</td>
<td>See Equation (4-13)</td>
</tr>
<tr>
<td>ALP4</td>
<td>R</td>
<td>1</td>
<td>-</td>
<td>See Equation (4-7)</td>
</tr>
<tr>
<td>ALP5</td>
<td>R</td>
<td>1</td>
<td>-</td>
<td>See Equation (4-7)</td>
</tr>
<tr>
<td>KDAY1</td>
<td>I</td>
<td>1</td>
<td>-</td>
<td>Days of the water year which are used as indices to change the value of ALP5 as a result of the seasonal variations in climate</td>
</tr>
<tr>
<td>KDAY2</td>
<td>I</td>
<td>1</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>BETAl</td>
<td>R</td>
<td>1</td>
<td>-</td>
<td>See Equation (4-15b)</td>
</tr>
<tr>
<td>BETA2</td>
<td>R</td>
<td>1</td>
<td>-</td>
<td>See Equation (4-17)</td>
</tr>
<tr>
<td>BETA3</td>
<td>R</td>
<td>1</td>
<td>-</td>
<td>See Equation (4-11)</td>
</tr>
<tr>
<td>BETA4</td>
<td>R</td>
<td>1</td>
<td>-</td>
<td>See Equation (4-13)</td>
</tr>
<tr>
<td>BETA5</td>
<td>R</td>
<td>1</td>
<td>-</td>
<td>See Equation (4-9)</td>
</tr>
<tr>
<td>BETA6</td>
<td>R</td>
<td>1</td>
<td>-</td>
<td>See Equation (4-9)</td>
</tr>
<tr>
<td>AISS</td>
<td>R</td>
<td>1</td>
<td>tons</td>
<td>Amounts of accretion in total loose particles storage other than those due to raindrop splash</td>
</tr>
<tr>
<td>ISST1</td>
<td>I</td>
<td>1</td>
<td>-</td>
<td>Approximate dates accretions in storage of the amount AISS take place</td>
</tr>
<tr>
<td>ISST2</td>
<td>I</td>
<td>1</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>DSSE</td>
<td>R</td>
<td>366</td>
<td>tons</td>
<td>Daily synthesized sheet erosion</td>
</tr>
<tr>
<td>SCOUR</td>
<td>R</td>
<td>366</td>
<td>tons</td>
<td>Daily amounts of channel bed and banks scouring</td>
</tr>
<tr>
<td>DSSL</td>
<td>R</td>
<td>366</td>
<td>tons</td>
<td>Daily synthesized suspended sediment loads</td>
</tr>
</tbody>
</table>
CHAPTER V. SIMULATION RESULTS -- FOUR MILE CREEK WATERSHED NEAR TRAER, IOWA

This chapter describes the application of the sheet erosion model to the Four Mile Creek watershed near Traer, Iowa. Figure 12 shows the map of the watershed. A brief description of the watershed is given below. This description also includes a summary of the hydrological characteristics related to this study as well as a list of the records used in the simulation study.

Description of the Watershed

Location: Tama County, Iowa. The center of the watershed is about 7 miles northwest of Traer, Iowa (see Figure 13)

Area: 19.51 square miles

Average Annual Rainfall: 32.5 inches

Average Annual Runoff: 10.6 cfs or 7.38 inches per year (based on 9 years of records)

Vegetal cover: Mostly row crops and meadow, small grains in small fields.

Soil type: Silt loam, moderate to thick in depth, loess-derived.

Summary of Available Records:

Runoff: October, 1962 to date. Maximum and minimum discharges recorded are 628.0 and 0.2 cfs, respectively. Records are good except for those for the winter period which are poor. (Source: U.S. Geological Survey)
Figure 12. Four Mile Creek watershed near Traer, Iowa
recording raingage
recording raingage and temperature
storage raingage and temperature
pan evaporation and solar radiation
pan evaporation

Figure 13. Location of the watershed and the sources of climatological information
Rainfall: Recording raingage at Traer, Iowa. Measurements date back prior to 1962 and continuing at present. (Source: U.S. Weather Bureau)

Sediment: Daily suspended loads from October, 1969 to date. (Source: U.S. Geological Survey)

Evaporation: The nearest stations with pan evaporation records are those located at Ames and Iowa City. Measurements date back prior to 1962 and continuing at present. (Source: U.S. Weather Bureau)

Solar radiation: The nearest measuring station is located at Ames, Iowa. Measurements date back prior to 1962 and continuing at present. (Source: U.S. Weather Bureau)

Temperature: Minimum and maximum temperature data are measured at nearby stations as shown on Figure 13. These stations are located at Grundy Center, Marshalltown, Toledo, and Vinton. The annual mean temperature for the watershed is about 48°F. (Source: U.S. Weather Bureau)

Streamflow Simulation Results

The first step in the suspended sediment load simulation procedure is the application of modified Kentucky Watershed Model to the watershed. The watershed parameters were estimated using the guidelines suggested in Chapter III. The possible application of the self-calibrating version (OPSET) of the Stanford Watershed Model in estimating some of the watershed parameters was first explored.

The three water years starting from 1963 through 1965 were used to evaluate the feasibility of using OPSET. The results were inconclusive as a result of the shortcomings of
OPSET as mentioned in Chapter III. Furthermore, the OPSET Fortran programs have not yet been fully debugged and they did not work satisfactorily for two of the three water years. Consequently, the use of OPSET was abandoned because of the enormous amount of time needed to modify and debug it. One water year of calibration using OPSET costs 50 dollars or more. A corresponding computer run using the Kentucky Watershed Model costs approximately four dollars. The watershed parameters that cannot be measured directly were, therefore, estimated by fitting or trial and error.

The watershed model was calibrated using the 1969 and 1970 water years. In the calibration process, more emphasis was given to the 1970 water year since this was also the same water year for which the sheet erosion model was to be calibrated. Only a few calibration runs were made using the 1969 water year. The 1971 water year was used as a test water year for both the watershed and the erosion models.

The best estimates of the Four Mile Creek watershed parameters are listed on Table 2. In addition to these parameters, estimates must also be made of the ratios of evapotranspiration to pan evaporation at various periods throughout the water year. These ratios were estimated using the research findings of Denmead and Shaw (1959) and Shaw (1963). These ratios as shown on Table 3 were estimated using the corn crop as the standard since it is the predominant crop
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>BDDFSM</td>
<td>0.0008</td>
<td>FIMP</td>
<td>0.025</td>
<td>OFSS</td>
<td>0.05</td>
</tr>
<tr>
<td>SPBFLW</td>
<td>0.05</td>
<td>FWTR</td>
<td>0.000</td>
<td>CHCAP</td>
<td>350.0</td>
</tr>
<tr>
<td>SPTWCC</td>
<td>0.25</td>
<td>VINTMR</td>
<td>0.15</td>
<td>OFMN</td>
<td>0.038</td>
</tr>
<tr>
<td>SPM</td>
<td>1.15</td>
<td>BUZC</td>
<td>1.00</td>
<td>OFMNIS</td>
<td>0.150</td>
</tr>
<tr>
<td>ELDIF</td>
<td>0.00</td>
<td>SUZC</td>
<td>1.70</td>
<td>IFRC</td>
<td>0.35</td>
</tr>
<tr>
<td>XNDFS</td>
<td>0.10</td>
<td>LZC</td>
<td>12.00</td>
<td>CSRX</td>
<td>0.98</td>
</tr>
<tr>
<td>FFOR</td>
<td>0.00</td>
<td>ETLF</td>
<td>0.30</td>
<td>FSRX</td>
<td>0.98</td>
</tr>
<tr>
<td>FFSI</td>
<td>0.10</td>
<td>SUBWF</td>
<td>0.00</td>
<td>EXQPV</td>
<td>0.20</td>
</tr>
<tr>
<td>MRNSM</td>
<td>0.12</td>
<td>GWETF</td>
<td>0.10</td>
<td>BFNLR</td>
<td>1.000</td>
</tr>
<tr>
<td>DSMGH</td>
<td>0.00</td>
<td>SIAC</td>
<td>2.00</td>
<td>BFRNC</td>
<td>0.973</td>
</tr>
<tr>
<td>PXCASA</td>
<td>0.05</td>
<td>BMTR</td>
<td>8.00</td>
<td>GFIE</td>
<td>5.0</td>
</tr>
<tr>
<td>RGPMB</td>
<td>1.00</td>
<td>BIVF</td>
<td>0.00</td>
<td>NDTUZ</td>
<td>75</td>
</tr>
<tr>
<td>AREA</td>
<td>19.51</td>
<td>OFSL</td>
<td>600.0</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

within the watershed. Instead of being used as variable inputs into the watershed model, these ratios are incorporated into the computer programs (MAIN0333-0340) as they are constants within the watershed for all the water years studied. They must be modified, however, if the watershed model is to be used in places where the climate and the cropping patterns are different from those existing within
Table 3. Ratio of evapotranspiration to pan evaporation throughout the water year\(^a\)

<table>
<thead>
<tr>
<th>Period during the water year(b)</th>
<th>Ratio</th>
<th>Period during the water year</th>
<th>Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>From day 1 through 150</td>
<td>0.35</td>
<td>From day 228 through 243</td>
<td>0.71</td>
</tr>
<tr>
<td>From day 151 through 165</td>
<td>0.41</td>
<td>From day 244 through 265</td>
<td>0.61</td>
</tr>
<tr>
<td>From day 166 through 181</td>
<td>0.47</td>
<td>From day 266 through 365</td>
<td>0.35</td>
</tr>
<tr>
<td>From day 182 through 196</td>
<td>0.67</td>
<td>Day 366</td>
<td>0.35</td>
</tr>
<tr>
<td>From day 197 through 227</td>
<td>0.80</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\(^a\)For the period from day 1 through 150 and from day 266 through 366 a constant ratio was assumed. For the winter period where the ground is frozen and/or there is snow on the ground this ratio is not used as snow evaporation estimates are used instead.

\(^b\)January 1 = day 1
December 31 = day 365
February 29 = day 366.
the watershed.

The ordinates of the time-area histogram estimated for the watershed are given on Table 4. These estimates are based on the following equation for the time of concentration

\[ T_c = 0.0078 \, L^{0.77} \, S^{-0.385} \]

where

\( T_c \) = time of concentration in minutes

\( L \) = maximum horizontal length of flow measured along the stream in feet

\( S \) = slope in feet per foot or the difference in elevation between the outlet and the most remote point divided by the length, \( L \).

<table>
<thead>
<tr>
<th>Travel time in minutes</th>
<th>Area ratio</th>
<th>Travel time in minutes</th>
<th>Area ratio</th>
<th>Travel time in minutes</th>
<th>Area ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.0094</td>
<td>135</td>
<td>0.0502</td>
<td>270</td>
<td>0.0536</td>
</tr>
<tr>
<td>15</td>
<td>0.0231</td>
<td>150</td>
<td>0.0587</td>
<td>285</td>
<td>0.0613</td>
</tr>
<tr>
<td>30</td>
<td>0.0288</td>
<td>165</td>
<td>0.0438</td>
<td>300</td>
<td>0.0434</td>
</tr>
<tr>
<td>45</td>
<td>0.0202</td>
<td>180</td>
<td>0.0373</td>
<td>315</td>
<td>0.0367</td>
</tr>
<tr>
<td>60</td>
<td>0.0239</td>
<td>195</td>
<td>0.0344</td>
<td>330</td>
<td>0.0300</td>
</tr>
<tr>
<td>75</td>
<td>0.0322</td>
<td>210</td>
<td>0.0442</td>
<td>345</td>
<td>0.0373</td>
</tr>
<tr>
<td>90</td>
<td>0.0283</td>
<td>225</td>
<td>0.0540</td>
<td>360</td>
<td>0.0352</td>
</tr>
<tr>
<td>105</td>
<td>0.0373</td>
<td>240</td>
<td>0.0460</td>
<td>375</td>
<td>0.0296</td>
</tr>
<tr>
<td>120</td>
<td>0.0370</td>
<td>255</td>
<td>0.513</td>
<td>390</td>
<td>0.0128</td>
</tr>
<tr>
<td>135</td>
<td></td>
<td>270</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Figure 14 shows the comparisons between the simulated and recorded average daily streamflows for the calibration water year of 1970 while those for the test water year of 1971 are shown on Figure 15. Table 5 shows the monthly and annual simulated and recorded streamflows for the water years from 1969 through 1971. The daily simulated and recorded streamflow values are tabulated on Appendix D.

From Figures 14 and 15 it is seen that the highest peaks are due to snowmelt. The watershed model tends to over-synthesize the snowmelt runoff peaks. As a result, the small streamflows are slightly undersynthesized so as to balance the incoming and outgoing moisture supply. These results indicate the need for a more comprehensive snowmelt subroutine. There are, however, serious limitations to any attempt to accomplish such a task. The major one is the scarcity of climatological data such as incident solar radiation.

Another limitation to any serious attempt at snowmelt modeling is the absence of factual information on the parameters governing snowmelt. Furthermore, the quality of the streamflow records are poor during the winter period as a result of the ice effect on the flow measurement. For this reason, no serious attempt has been made to develop a comprehensive snowmelt subroutine in this study.

The simulated streamflow values for the months of August and September are slightly higher than the recorded flows. Since these are low flow months, the discrepancies between
Figure 14. Mean daily recorded and simulated streamflows for the Four Mile Creek watershed near Traer, Iowa for the 1970 water year.
Figure 14 (Continued)

R = Recorded
S = Simulated
Figure 15. Mean daily recorded and simulated streamflow for the Four Mile Creek watershed near Traer, Iowa for the 1971 water year.
Figure 15 (Continued)

R = Recorded
S = Simulated
Table 5. Monthly and annual recorded and simulated streamflows for Four Mile Creek watershed near Traer, Iowa

<table>
<thead>
<tr>
<th>Month</th>
<th>Water year 1969 Streamflow, cfs days</th>
<th>Water year 1970 Streamflow, cfs days</th>
<th>Water year 1971 Streamflow, cfs days</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Recorded</td>
<td>Simulated</td>
<td>Recorded</td>
</tr>
<tr>
<td>October</td>
<td>213.3</td>
<td>336.0</td>
<td>118.1</td>
</tr>
<tr>
<td>November</td>
<td>101.7</td>
<td>260.4</td>
<td>124.9</td>
</tr>
<tr>
<td>December</td>
<td>300.0</td>
<td>451.0</td>
<td>68.6</td>
</tr>
<tr>
<td>January</td>
<td>283.6</td>
<td>136.0</td>
<td>48.0</td>
</tr>
<tr>
<td>February</td>
<td>238.6</td>
<td>157.6</td>
<td>807.4</td>
</tr>
<tr>
<td>March</td>
<td>1,778.7</td>
<td>961.4</td>
<td>721.7</td>
</tr>
<tr>
<td>April</td>
<td>1,067.0</td>
<td>1,448.0</td>
<td>216.8</td>
</tr>
<tr>
<td>May</td>
<td>878.0</td>
<td>1,406.0</td>
<td>516.2</td>
</tr>
<tr>
<td>June</td>
<td>1,363.0</td>
<td>1,013.7</td>
<td>183.1</td>
</tr>
<tr>
<td>July</td>
<td>1,979.8</td>
<td>1,327.4</td>
<td>53.1</td>
</tr>
<tr>
<td>August</td>
<td>432.3</td>
<td>509.5</td>
<td>92.0</td>
</tr>
<tr>
<td>September</td>
<td>130.0</td>
<td>207.4</td>
<td>140.0</td>
</tr>
<tr>
<td>Total</td>
<td>8,766.0</td>
<td>8,216.2</td>
<td>3,089.9</td>
</tr>
</tbody>
</table>

Daily Correlation Coefficient 0.68 0.96 0.76
the simulated and recorded streamflows are insignificant when compared to the streamflows for the rest of the months within the water year. In general, the simulated average daily streamflows compared quite favorably with the recorded flow values for the 1970 and 1971 water years. Although the daily correlation coefficient for the 1969 water year is quite low, the monthly and annual simulated streamflows are comparable to the recorded values.

Aside from the errors inherent in the watershed model itself, the input climatological data are also sources of errors in the simulation of streamflows. For the Four Mile Creek watershed, the pan evaporation values were estimated by averaging the measured values from the measuring stations at Ames and Iowa City (see Figure 13). The estimates of the incident solar radiation were also based on the recorded values for Ames, Iowa.

The hourly rainfalls used were those recorded at Traer, Iowa which is about 7.5 miles from the center of the watershed. The variations in the rainfall amounts representative of the watershed and those measured at the recording gage at Traer, Iowa have been studied by Ruhe and Vreeken (1969). Their study showed that during the period from January 1, 1963 through March 31, 1967, precipitation was recorded 367 times on the Traer region. Rain was recorded 30 times at a storage rain-gage in the watershed but not at the Traer station and was
recorded 48 times at the Traer station but not at the storage gage in the watershed. The two raingages are only about 4.5 miles away from each other. Additional yearly rainfall amounts recorded at the Traer station but not at the gage in the watershed are 0.73 in 1963, 0.61 in 1964, 0.89 in 1965, and 0.41 in 1966. From these figures it is obvious that there are also significant variations in the rainfall intensities and distributions between the two stations.

Results of Simulation of Suspended Sediment

The sheet erosion model was calibrated by trial and error using the 1970 water year. The best estimates of the sheet erosion model parameters are given in Table 6. The calibrated sheet erosion model was then tested on the test water year of 1971. Since only two water years of suspended sediment records are available, the calibration as well as testing of the sheet erosion model on two or more water years is not possible on Four Mile Creek watershed. Such extensive calibration and testing of the sheet erosion model, though feasible for other watersheds, has not been attempted because of prohibitive costs in terms of data collection and computer execution time.

Figure 16 shows the simulated and recorded daily suspended sediment loads for the calibration water year of 1970 while those for the test water year of 1971 are shown on Figure 17.
Table 6. Estimated sheet erosion parameters for the Four Mile Creek watershed near Traer, Iowa

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALP1</td>
<td>2.00</td>
<td>KDAY1</td>
<td>70</td>
</tr>
<tr>
<td>ALP2</td>
<td>1.50</td>
<td>KDAY2</td>
<td>360</td>
</tr>
<tr>
<td>ALP3</td>
<td>1.33</td>
<td>BETA1</td>
<td>20.0</td>
</tr>
<tr>
<td>ALP4</td>
<td>0.02</td>
<td>BETA2</td>
<td>625.0</td>
</tr>
<tr>
<td>ALP5</td>
<td>80.0</td>
<td>BETA3</td>
<td>833.0</td>
</tr>
<tr>
<td>ISST1</td>
<td>61</td>
<td>BETA4</td>
<td>0.150</td>
</tr>
<tr>
<td>ISST2</td>
<td>400</td>
<td>BETA5</td>
<td>41,600.0</td>
</tr>
<tr>
<td>AISS</td>
<td>3120.0</td>
<td>BETA6</td>
<td>3.50</td>
</tr>
</tbody>
</table>

Table 7 gives the monthly and annual simulated and recorded suspended sediment loads for both water years.

The two main sources of suspended sediment loads are sheet erosion and channel scour. These components as computed by the sheet erosion model are compared in Figure 18 which shows the daily simulated sheet and channel scour erosion rates for the 1970 water year. Similar data for the test water year of 1971 are shown on Figure 19. Table 8 shows the simulated monthly and annual sheet and scour erosion rates for both water years. The daily, monthly, and annual simulated and recorded sediment loads are shown in Appendix E.
Figure 16. Daily recorded and simulated suspended sediment loads for the Four Mile Creek watershed near Traer, Iowa for the 1970 water year.

R = Recorded
S = Simulated
Figure 16 (Continued)

R = Recorded
S = Simulated

Daily suspended sediment loads in tons
R = Recorded
S = Simulated

Figure 17. Daily recorded and simulated suspended sediment loads for the Four Mile Creek watershed near Traer, Iowa for the 1971 water year.
Figure 17 (Continued)

Daily suspended sediment loads in tons

R = Recorded
S = Simulated

April May June July August September

0 500 1000 1500 2000 2500
Figure 18. Daily simulated sheet and channel scour erosion rates for Four Mile Creek watershed near Traer, Iowa for the 1970 water year

se = sheet erosion
cs = channel scour
se = sheet erosion
cs = channel scour

Figure 18 (Continued)
Figure 19. Daily simulated sheet and channel scour erosion rates for Four Mile Creek watershed near Traer, Iowa for the 1971 water year

se = sheet erosion
cs = channel scour
Figure 19 (Continued)

se = sheet erosion

cs = channel scour
Table 7. Monthly and annual recorded and simulated suspended sediment loads for Four Mile Creek watershed near Traer, Iowa

<table>
<thead>
<tr>
<th></th>
<th>Water year 1970</th>
<th>Water year 1971</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Suspended sediment</td>
<td>Suspended sediment</td>
</tr>
<tr>
<td></td>
<td>loads, tons</td>
<td>loads, tons</td>
</tr>
<tr>
<td></td>
<td>Recorded</td>
<td>Simulated</td>
</tr>
<tr>
<td>October</td>
<td>41.07</td>
<td>59.80</td>
</tr>
<tr>
<td>November</td>
<td>27.29</td>
<td>31.20</td>
</tr>
<tr>
<td>December</td>
<td>15.31</td>
<td>13.70</td>
</tr>
<tr>
<td>January</td>
<td>11.01</td>
<td>9.70</td>
</tr>
<tr>
<td>February</td>
<td>326.50</td>
<td>553.00</td>
</tr>
<tr>
<td>March</td>
<td>1,816.10</td>
<td>2,976.60</td>
</tr>
<tr>
<td>April</td>
<td>30.20</td>
<td>106.10</td>
</tr>
<tr>
<td>May</td>
<td>1,857.84</td>
<td>1,651.00</td>
</tr>
<tr>
<td>June</td>
<td>53.14</td>
<td>177.40</td>
</tr>
<tr>
<td>July</td>
<td>10.03</td>
<td>89.80</td>
</tr>
<tr>
<td>August</td>
<td>109.07</td>
<td>113.40</td>
</tr>
<tr>
<td>September</td>
<td>135.23</td>
<td>209.10</td>
</tr>
<tr>
<td>Total</td>
<td>4,432.61</td>
<td>5,990.80</td>
</tr>
</tbody>
</table>

Correlation Coefficient (Daily) 0.85 0.90
Table 8. Monthly and annual simulated sheet and channel scour erosion rates for the Four Mile Creek watershed near Traer, Iowa

<table>
<thead>
<tr>
<th>Month</th>
<th>Water year 1970</th>
<th>Water year 1971</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>soil loss, tons</td>
<td>soil loss, tons</td>
</tr>
<tr>
<td></td>
<td>sheet erosion</td>
<td>channel scour</td>
</tr>
<tr>
<td>October</td>
<td>31.5</td>
<td>28.3</td>
</tr>
<tr>
<td>November</td>
<td>1.2</td>
<td>30.0</td>
</tr>
<tr>
<td>December</td>
<td>0.0</td>
<td>13.7</td>
</tr>
<tr>
<td>January</td>
<td>0.8</td>
<td>8.9</td>
</tr>
<tr>
<td>February</td>
<td>25.0</td>
<td>528.0</td>
</tr>
<tr>
<td>March</td>
<td>2,505.2</td>
<td>471.4</td>
</tr>
<tr>
<td>April</td>
<td>43.4</td>
<td>62.7</td>
</tr>
<tr>
<td>May</td>
<td>1,408.3</td>
<td>242.7</td>
</tr>
<tr>
<td>June</td>
<td>126.3</td>
<td>51.1</td>
</tr>
<tr>
<td>July</td>
<td>80.1</td>
<td>9.7</td>
</tr>
<tr>
<td>August</td>
<td>88.6</td>
<td>24.8</td>
</tr>
<tr>
<td>September</td>
<td>166.4</td>
<td>42.7</td>
</tr>
<tr>
<td>Total</td>
<td>4,476.8</td>
<td>1,514.0</td>
</tr>
</tbody>
</table>

Table 7 shows that most of the annual soil loss occurred during the period from February through May. During these months the soil surface is bare and the soil is usually at or near field moisture capacity. Hence, these are usually the months of high overland flows. From June through October, the influence of vegetation becomes more pronounced. Runoff
events are usually of low magnitude as a result of increased rainfall interception and higher evapotranspiration rates. As a result, the soil loss rates during this period are relatively low.

The relative proportion of sheet erosion to the total annual soil loss is highly dependent on the characteristics of the individual runoff events as well as their distribution throughout the water year. During the winter period this proportion will be small if the precipitation is in the form of snow. In such a case detachment by rainfall is zero and the availability of loose soil particles in storage (TSST) is the limiting factor to sediment transportation. Under such a condition, channel scour becomes the relatively more significant source of suspended sediment load. It must be pointed out, however, that if significant precipitation in the form of rain occurs simultaneously with snowmelt, sheet erosion will be the more significant source of suspended sediment load. This was the case during the first week in March of 1970.

During the period of the water year from May through October, most of the suspended sediment load comes from sheet erosion (see Table 8). For this period, the percentages of the total suspended sediment load coming from sheet erosion are 83 and 63 per cent for the 1970 and 1971 water years, respectively. For the period from November
through January there is very little runoff due to either rain or snowmelt.

Generally, the sediment simulation results for the test watershed are fair considering the complexity of the soil erosion process. In comparing the simulated to the recorded sediment loads, it is to be noted that some of the apparent discrepancies may be due to errors in the recorded data themselves. As pointed out by Negev (1967), these errors may be due to (1) an insufficient number of sampling verticals to define the true average concentration in a cross section and (2) insufficient number of measurements to define the true time average concentration. Benedict et al. (1955) found that errors due to the first and second causes could be as high as 25 and 85.3 per cent, respectively.

The simulated loads for the 1971 water year are lower than the recorded loads. Most of this discrepancy occurred during the three-day period from March 12 through 14 when approximately one-half of the total recorded annual suspended sediment load was observed. This points toward some inherent errors in the erosion model in itself. Since no significant rainfall was recorded during this three-day period, the most likely source of error is the channel scouring component of the erosion model. It is to be noted that the channel scouring component of the erosion model uses the average daily recorded streamflows instead of hourly or
quarter-hourly streamflows. Since the expression relating
channel scour to streamflow is of the exponential form,
errors due to such time averaging are to be expected.

In reviewing the errors detected in the simulated sus­
pended sediment load, the errors associated with recorded
streamflows must not be overlooked. It is to be noted that
the quality of the runoff records during the winter months
of January, February, and March are classified as poor due
to the effect of ice on the streamflows. Since the recorded
suspended sediment load is computed by multiplying the mean
water discharge during a time interval by the concentration
of the suspended material measured during that time, the
errors in the streamflow estimates will be transferred to the
suspended sediment load data.

The discrepancies between the recorded and simulated
sediment loads may also be due to the fact that the hourly rain­
fall amounts were taken from a raingage located outside the
catchment area. It is apparent from Equation (4-4) that the
amounts of soil detached by raindrops is highly dependent on
the assumed hourly rainfalls. In addition, the hourly or
quarter-hourly overland flows as computed by the watershed
model are dependent on the assumed hourly rainfalls.
Application of the Model to the Skunk River Watershed near Ames, Iowa

As the study of the Four Mile Creek watershed neared completion, the sedimentation hazards on the Skunk River above Ames, Iowa needed to be evaluated. This is in connection with the environmental resources study of the proposed Ames reservoir. This study is currently being conducted jointly by the Iowa State University and the State University of Iowa. Exploratory simulation studies on the Skunk River are currently being conducted using the proposed sheet erosion model.

A map of the watershed showing the locations of the streamflow gaging stations below Ames and upstream of Ames and the raingages is shown on Figure 20. The dam site for the proposed reservoir is adjacent to the upstream gaging station which has a drainage area of 315 square miles. Since there are no suspended sediment load records available on the upstream gaging station, the larger watershed represented by the gaging station below Ames is the one being used in the simulation attempts. This watershed has a drainage area of 556 square miles.

The preliminary simulation results were inconclusive. A problem was encountered in the streamflow simulation using the watershed model. The watershed is too large and the raingages are too few to obtain representative hourly rain-
Figure 20. Skunk River watershed near Ames, Iowa
falls for the entire watershed. Large discrepancies in the measured rainfalls have been observed between the two recording raingages at Ames and Webster City. The storage raingage at Jewell also showed greater recorded rainfall discrepancies when compared with that at Ames which is less than 30 miles away. For example, during the month of June, 1968, the Ames station recorded 9.09 inches of rain while the Jewell station recorded only 0.13 inches.

Another difficulty encountered in the simulation attempt was evaluating the quality of the suspended sediment load records. Suspended sediment load measurements are available for the water years from 1968 through 1971. These measurements were, however, usually taken at weekly or bi-weekly intervals. The daily sediment loads for the rest of the week have to be roughly approximated.

The existence of many surface depressions or potholes on the upper sections of the watershed poses some difficulties in the simulation attempts. The presence of these potholes as well as the size of the watershed point toward the need for watershed segmentation using perhaps a different watershed model for each segment. However, even if time and effort are available for such a segmentation study, the scarcity of raingages within the watershed will still prove to be a serious drawback in simulating the streamflows and sediment loads from the watershed.
Although the Four Mile Creek watershed and the Skunk River watershed represented by the streamgage below Ames are only about 60 miles apart, the differences in size, topographic features, and in geology between the two watersheds limit the application of the simulation results from the former to the latter watershed. Most of the Skunk River watershed parameters required by sheet erosion as well as the watershed model would need to be evaluated by fitting or trial and error.
CHAPTER VI. SUMMARY AND CONCLUSIONS

A sheet erosion model on a digital computer was developed to simulate suspended sediment loads on small agricultural watersheds. The model is used in conjunction with a modified version of the Stanford Watershed Model. To evaluate its feasibility, the erosion model was tested on the Four Mile Creek watershed near Traer, Iowa. Four Mile Creek is an agricultural watershed having a drainage area of 19.51 square miles.

The first step in using the sheet erosion model is the calibration of the watershed model. The watershed model used was the Kentucky Watershed Model (KWM) which is a modified version of the Stanford Watershed Model. The essentials of the KWM were presented in Chapter III. The watershed model was calibrated using the 1969 and 1970 water years. The calibrated watershed model was then tested on the 1971 water year and the simulation results were summarized in Chapter V.

The essentials of the proposed sheet erosion model were presented in Chapter IV. The model was calibrated for the Four Mile Creek watershed using the 1970 water year. It was then tested using 1971 as the test water year. The suspended sediment load simulation results were reported in Chapter V. This chapter presents the conclusions derived from the
exploratory simulation results and analyzes the errors involved in them.

On the basis of the results from this study, the following conclusions were made:

1. The erosion model will reproduce, within a 35 per cent error, annual, monthly, and daily suspended sediment loads from the test watershed if accurate overland flow values can be synthesized by the accompanying watershed model.

2. With some modifications and adaptations to the existing watershed conditions, the Kentucky Watershed Model will simulate annual, monthly, and daily streamflows from the test watershed within a 30 per cent error.

3. The occurrence of snowmelt is a serious problem with the Kentucky Watershed Model. The model has to be modified to include a working snowmelt subroutine if consistent and accurate streamflow simulation results are to be obtained with its use in places where snowmelt runoff is significant. The snowmelt subroutine listed in Appendix A has been found to yield inconsistent results from one water year to another. For this same reason, the self-calibrating version of the KWM was found to be unapplicable to the test watershed.

3. The sheet erosion model cannot be applied to large watersheds. Preliminary studies with the 556 square mile South Skunk River north of Ames, Iowa indicate that with a large watershed, it is not possible to obtain representative
hourly rainfall and, hence, overland flow values for the watershed. Since most of the components of both the watershed and erosion models are based on nonlinear relationships, averaging rainfall and overland flow values presents a very serious limitation. This points toward the need for watershed segmentation which is not provided for in the Kentucky Watershed Model.

4. A serious drawback in using the Kentucky Watershed Model is the great amount of time required to become acquainted with it in order to interpret its outputs. Understanding the model is essential to the proper adjustment of the watershed parameters.

5. The most serious limiting factor to further development and evaluation of the proposed erosion model lies on the accompanying watershed model. The watershed model size dictates that a high speed and large storage digital computer be available. In order to become familiarized with the watershed model and determine the best basin parameters much computer time is required. Experience on the Four Mile Creek watershed indicates that as many as 40 computer runs may be needed to calibrate the model. The computer execution time needed to simulate one water year of data is about 35 seconds. This is equivalent to about five dollars at the current commercial rate at the Iowa State University Computation Center. Thus calibrating the watershed model for several water years
for each of several test watersheds can be costly.

6. The calibration of the sheet erosion model after the watershed model may require 20 computer runs or more. Because much computer time is required no serious attempts to conduct sensitivity studies on the sheet erosion parameters have been made.

7. As a final conclusion, it is felt that from the basis of the results presented in Chapter V that the sheet erosion model (when used with the Stanford Watershed Model or its kind), appears to form a sound and workable foundation for erosion simulation works.

The errors in the simulation studies may be caused by the following:

1. Deficiencies in the sheet erosion model. Obviously, some of the errors in the simulation attempts result from the deficiencies in the sheet erosion model itself. One of the probable deficiencies in the model is the assumption that the channel bank caving and bed scouring component of the model is a simple power function of the mean daily recorded flows. Since for a given average daily streamflow various types of daily runoff hydrographs are possible, errors due to such time averaging are to be expected. Another apparent deficiency in the model is its lack of a gully erosion component. Gully erosion is a complex process and no satisfactory equations describing this process are available.
Other deficiencies that can be attributed to the model include the lack of components describing sediments deposition along the flood plain and the lack of sufficient parameters to define the seasonal effects on some of the sheet erosion parameters. Also, the expressions for rainfall detachment and transport as well as overland flow scouring used in the model were approximations that need further improvements. The correction of some or all of the above deficiencies would, of course, require more time and data than are available for this study.

2. Errors in the recorded daily streamflows. These errors may result from insufficient number of samples to define the average streamflows, changes in the channel geometry near the gaging station as a result of channel aggradation and degradation, and ice effect on the streamflow measurements during the winter period.

3. Errors in the recorded suspended sediment loads. As mentioned before, these errors may be due to the inadequacy of the sediment sampling procedure to define the true average sediment concentration in the stream at all times. They may also be due to the errors in the streamflow data which are used in estimating the average daily suspended sediment loads.

4. Errors due to nonrepresentative hourly rainfalls and overland flows. The hourly rainfalls are the most
critical inputs to the sheet erosion model. Not only are they used to estimate the rainfall detachment and transport functions in the erosion model but they are also used by the watershed model to synthesize the overland flow values. The hourly rainfall values used in the Four Mile Creek simulation study were taken from a recording raingage located outside and about 7.5 miles from the center of the watershed. A study of Ruhe and Vreeken (1969) has shown that these hourly rainfalls do not represent those within the watershed at all times.
CHAPTER VII. SUGGESTIONS FOR FURTHER RESEARCH

Due to the exploratory nature of this study, numerous possible extensions of it are evident. Some possible improvements in the watershed model were mentioned in Chapter VI in presenting the conclusions from this study. Some possible improvements in the sheet erosion model were also mentioned in Chapter VI in discussing the deficiencies of the model. Other possible extensions include the following.

1. There is a need for a comprehensive mathematical submodel of the rainfall detachment process. Such a model may be based on a much more detailed form of Equation (4-5). It should include the influence of rainfall and soil characteristics, particularly as they vary with time.

2. The expressions for rainfall detachment and transport functions of the sheet erosion model were approximations based on a detailed review of currently available information. Improved relationships based on further experimental research are needed.

3. There is a need to investigate the contribution of raindrop and prerill flow detachment as compared to the contribution of rill flow detachment in making up the total sheet erosion losses. The mechanics of sediment delivery to rills by rainfall and prerill overland flow is an important phase of the sheet erosion process which has not been fully
described. Consequently, there is a question as to the conditions under which detachment is limiting on these un-rilled sections versus those conditions where transport is limiting.

4. The application of the sheet erosion model to larger watersheds should be developed. A small watershed, for convenience, may be defined as one having a drainage area of less than 100 square miles. Large watersheds should be segmented and the outputs of the individual segments should then be combined.

5. The erosion model should be tested in other regions to further evaluate its feasibility. Tests on watersheds with two or more distinct rainfall seasons and on those undergoing some urbanization may disclose the need for further model modifications.
REFERENCES


Ruhe, R. V. and W. J. Vreeken. 1969. Hydrologic system related to geology and soils, Four Mile Creek area, Tama County, Iowa. Iowa State University of Science and Technology Water Resources Research Institute Completion Report.


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APPENDIX A. LISTING OF WATERSHED AND SHEET EROSION MODELS
LISTING OF WATERSHED AND SHEET EROSION MODELS

C SHEET EROSION MODEL WILLIE DAVID FEBRUARY, 1972
C SUPERIMPOSED ON THE KENTUCKY WATERSHED MODEL OF JUNE 6, 1970
C WHICH IS BASED ON THE STANFORD WATERSHED MODELS III & IV
C
DIMENSION BTRI(99), CONOPT(20), CRFMI(22), CTRI(99), DDIW(366),
1 DMNT(366), DMXT(366), DPSE(366), DRGP6M(366), DRHP(366,24),
2 DRSGP(366), DPET(366), DRSF(366), DSSF(366), EDLZS(366),
3 EMBFNX(12), EMGWS(12), EMIFS(12), EMLS(12), EMSIAM(12),
4 EMUZC(12), EMUZS(12), EPCM(12), FIRRR(15), MECXY(12), MEDWY(12)
DIMENSION SATRI(99), SERA(22), SERR(22), SESF(22), SQER(22),
6 THSF(24), TITLE(20), TMBF(12), TMFSIL(12), TMIF(12), TMNET(12),
7 TMOF(12), TMPET(12), TMPREC(12), TMRPM(12), TMRTF(12), TMSE(12),
8 TMSE(12), TWSTF(12), TMSTFI(12), T200FHI(21), T20ORH(21),
9 UHFA(99), YTITLE(20), RICY(366), RWPD(12)
DIMENSION DRS(366),DSS(366),USFA(99),TSSF(24),SCOUR(366),
1 DSSE(366)
LOGICAL LSHFT
INTEGER CDSDR,CN,CONOPT,DATE,DAY,DPY,EHSGD,HOUR,HRF,HRL,PDAY,
1 PRD,RHD,RHPH,RSBD,SGMD,GRST,SGRT2,YEAR,RY1,RY2
REAL IFPCR,IFRC,IFRL,IFS,LZC,LZRX,LZS,LZSR,MHSM,MNRD,MRNSM,NHPT
CATA MECXY/ 0, 31,59,90,120,151,181,212,243,273,304,334/
DATA MEDWY/304,334,365,31,59,90,120,151,181,212,243,273
NYSD = 0
100 CONTINUE
READ(5,70)(CONCPT(I),I=1,20)
70 FORMAT(20I3)
DO 102 KIA = 1,99
SATRI(KIA) = 0.0
CTRI(KIA) = 0.0
BTRI(KIA) = 0.0
USFA(KIA) = 0.0
102 UHFA(KIA) = 0.0
READ(5,55) NYSD
BFRL = -ALOG(BFHR)
BFNRL = 0.0
IF(BFNRL .LT. 0.00001 .OR. BFNRL .GT. 0.9999) GO TO 111
BFNHR = BFNRL**(1.0/24.0)
BFNRL = -ALOG(BFNHR)
IF(BFNRL .LT. 0.00001 .OR. BFNHR = BFNRL**(1.0/24.0)
IFPRC = IFRC**(1.0/96.0)
IFRL = -ALOG(IFPRC)
READ(5,81) GWS,UZS,LZS,BFNX,IFS,GFIE,NDTZ
81 FORMAT(6F7.4,13)
IF(CONOPT(15).NE.1) GO TO 444
READ(5,303) ALP1,ALP2,ALP3,ALP4,ALP5,KDAY1,KDAY2
303 FORMAT(5F10.4,2I4)
READ(5,305) BETA1,BETA2,BETA3,BETA4,BETAS,BETA6
305 FORMAT(6F12.4)
307 FCMAT(2I4,F8.1)
CONTINUE
LSHFT = .FALSE.
IF(CONOPT(15).NE.1) GO TO 113 NBTRI = NCTRI
NBTRI = NCTRI
MXTRI = (10.0**EXQPV)*FNTRI + 0.5
IF(MXTRI .GE. 98) WRITE(6,1)
1 FORMAT(29HWARNING: EXQPV ARRAY OVER RUN)
NCSTRI = 99
DO 112 KIA = 1, NBTRI
BTRI(KIA) = CTRI(KIA)
TFCFS = 1.0
CALL RTVARY (CTRI,SATRI,BTRI,CHCAP,NBTRI,MXTRI,NCSTRI,EXQPV,LSHFT,
1 TFCFS)
113 EPAET = 0.0
FPER = 1.0 - FIMP - FWTR
IF(FPER .GT. 0.01) GO TO 114
TPLR = 100.0
FPER = 0.01
GO TO 115
TPLR = (1.0 - FWTR)/FPER
VINTCR = 0.25*VINTMR
HSE = 0.0
NRTR = 0
PEAI = 0.0
SPIF = 0.0
CBF = GWS*BFRL*(1.0 + BFNRL*BFNX)
SPDR = 0.0
OFUS = C.0
CFUSIS = 0.0
OFR = 0.0
OFRIS = 0.0
PEIS = 0.0
RHFO = C.0
RSOF0 = 0.0
URHF = 0.0
URSF = 0.0
TSST = 0.0
AMIF = C.0
AMNET = 0.0
AMPET = 0.0
AMSNE = 0.0
AMFSIL = 0.0
SASFX = 0.0
SARAX = 0.0
SRX = CSRX
VWIN = 26.8888*AREA
WCFS = 24.0*VWIN
RHFM = 0.025/WCFS
TFCFS = CBF*WCFS
SSRT = SQRT(OFSS)
OFRF = 1020.0*SSRT/(OFMN*OFSL)
OFRFIS = 1020.0*SSRT/(OFMNIS*OFSL)
EQOF = 0.00982*((OFMN*OFSL/SSRT)**0.6)
EQOFIS = 0.00982*((OFMNIS*OFSL/SSRT)**0.6)
SOFRF = OFRF
SOFRFI = OFRFIS
SDEPTH = 0.0
ASM = 0.0
IF(CONOPT(7) .EQ. 0) GO TO 116
WT4AM = 60.0
WT4PM = 60.0
SAX = 15.0
TANSM = 0.0
SPTW = 0.0
STMD = C.7
SFMD = C.7
ASMRG = 0.0
116 READ(5,2) TITLE
2 FCRMAT(20A4)
C BEGIN NEW YEAR
117 BYLZS = LZS
BYUZS = UZS
NYSD = NYSD + 1
BYGWS = GWS
BYIFS = IFS
DO 118 KIA = 1,22
CRFMI(KIA) = 0.0
SESF(KIA) = 0.0
SERR(KIA) = 0.0
SERA(KIA) = 0.0
118 SQER(KIA) = 0.0
RGPM = RGPMB
DO 119 KIA = 1,21
T200FH(KIA) = 0.0
119 T20PRH(KIA) = 0.0
DO 120 KIA = 1,12
EPCMI(KIA) = 1.0
ROPT = 0.0
PDAY = 274
READ(5,82) YR1,YR2
82 FORMAT(2I3)
READ (5,2) YTITLE
DPY = 365
IF(MOD(YR2,4) .EQ. 0) DPY = 366
IF(CONOPT(I) .EQ. 1) READ(5,67) CDSDR, NDSDR
67 FORMAT(2I4)
NDSDP = 0
MEDWY(5) = 59
IF(DPY .EQ. 366) MEDWY(5) = 366
C READ EVAPORATION DATA
IF(CONOPT(3) .NE. 1) GO TO 125
DO 121 KRD = 274,360,10
121 READ(5,83) DPET(KRD)
83 FORMAT(F5.3)
DO 122 KRD = 1,273,10
122 READ(5,83) DPET(KRD)
DO 124 ICAY2 = 274,360,10
DO 123 IDAY1 = 274,360,10
DAY = ICAY1 + IDAY2
123 DPET(DAY) = DPET(IDAY1)
DO 124 IDAY1 = 1,273,10
DAY = ICAY1 + IDAY2
IF(DAY .GT. 273) GO TO 124
DPET(DAY) = DPET(IDAY1)
124 CONTINUE
DPET(366) = DPET(59)
DPET(365) = DPET(363)
DPET(364) = DPET(363)
GO TO 127
125 READ(5,84) NDIM, NDFM
84 FORMAT(2I4)
NDIM2 = NDIM + 1
NDFM1 = NDFM - 1
DO 60 ICP = NDIM2, DPY
60 DPET(ICP) = 0.03
DO 61 IP = 1,60
61 DPET(IP) = 0.03
DO 62 IK = 61, NDFM
62 DPE'IK) = 0.15
   READ(5,85)(DPE'IK), DAY = NDFM, NANDM)
85 FCMAT(15F5.2)
127 IF(EPAET .NE. 0.0) GO TO 381
   DO 129 CAY = 1, DPY
   IF(EPAET .NE. 0.0) GO TO 381
   DO 129 CAY = 1, DPY
   EPAET = EPAET + 0.60 * DPE'IK)
   AETX = 24.0 + EPAET/365.0
   AEIX96 = 1.2*AETX
   AEIX90 = 0.3*AETX
   SIAM = 1.2**SIAC
   UZC = SUZC*AEIX90 + BUZC*EXP(-2.7*LZS/LZC)
   IF(UZC .LT. 0.25) UZC = 0.25
381 SGRT = C
   DO 132 CAY = 1, 366
   DDIW(DAY) = 0.0
   DRSF(DAY) = 0.0
   DRSL(DAY) = 0.0
   DRGPM(CAY) = RGPMB
   DRSGP(DAY) = 0.0
   DO 132 HOUR = 1, 24
132 DRHP(DAY, HOUR) = 0.0
133 IF(CONDPT(9) .NE. 1) GO TO 138
   DRSF(366) = 0.0
   READ(5, 66)(DRSF(DAY), DAY = 1, DPY)
   86 FORMAT(12F6.1)
138 IF(CONDPT(16) .NE. 1) GO TO 135
   DRSL(366) = 0.0
   READ(5, 300)(DRSL(DAY), DAY = 1, DPY)
300 FORMAT(8F10.2)
135 IF(CONDPT(ll) .NE. 1) GO TO 137
   DDIW(366) = 0.0
136 REAC(5, 86)(DDIW(DAY), DAY = 1, DPY)
137 IF(CONDPT(7) .EQ. 0) GO TO 139
   DO 65 I = 121, 304
65 RICY(I) = 48.0
READ(5,66)(RICY(CAY), DAY = 1,120)
READ(5,66)(RICY(DAY), DAY = 305,366)
66 FORMAT(13F6.1)
DO 68 IN = 121,304
DMXT(IN) = 80.0
68 DMNT(IN) = 60.0
READ(5,69)(DMXT(CAY), DAY = 1,120)
READ(5,69)(DMXT(DAY), DAY = 305,366)
READ(5,69)(DMNT(CAY), DAY = 1,120)
READ(5,69)(DMNT(DAY), DAY = 305,366)
69 FORMAT(15F5.1)
139 READ(5,87) NSGRD
87 FORMAT(13)
IF(NSGRC .EQ. 0) GO TO 141
READ(5,88) WSG,SGRT
88 FORMAT(F7.4, I3)
IF(CNCOPT .EQ. 1) READ(5,89) WSG2,SGRT2,SGMD
89 FORMAT(F7.4,2I3)
DO 140 KRD = 1,NSGRD
140 READ(5,90) ISGRD,DRSGP(ISGRD)
90 FORMAT(I3,F7.4)
C READ RECORDING RAIN GAGE HOURLY TOTALS
141 READ(5,91) YEAR,MONTH,DATE,CN,(RWPD(I), I = 1,12)
91 FORMAT(3I4,13,12F5.2)
C PUNCH NO NUMBER AFTER CN ON YEAR .EQ. 98 CARD
IF(YEAR .GE. 98) GO TO 144
HRF = 12*(CN - 1) + 1
HRL = 12*(CN - 1) + 12
LSD = HRF - 1
DAY = MEDCY(MONTH) + DATE
DO 142 HOUR = HRF, HRL
142 DRHP(CAY,HOUR) = RWPD(HOUR - LSD)
IF(DP .NE. 366 .OR. MONTH .NE. 2 .OR. DATE .NE. 29) GO TO 141
DO 143 HOUR = HRF, HRL
143 DRHP(60,HOUR) = 0.0
GO TO 141

CALCULATE PRECIPITATION WEIGHTING FACTORS

144  DAY = 274
    IF(NSGRC .EQ. 0) GO TO 151
    PDAY = 274
    RDPT = C.0
145  EHSGD = SGRT
    IF(SGRT .EQ. 0) EHSGD = 24
    E+SGDF = EHSGD
146  CONTINUE
    DO 150 HCUR = 1,24
        RDPT = RDPT + ORHP(DAY,HOUR)
        IF(HCUR .NE. EHSGD) GO TO 150
        IF(RDPT .LE. 0.0) GO TO 147
        IF(SGRT .EQ. 0) PDAY = DAY
        DRGPM (PDAY) = (DRSGP(DAY)*WSG + RDPT*(1.0 - WSG))/RDPT
        IF(CONOPT(3) .NE. 0) DPET(PDAY) = 0.5*DPET(PDAY)
        IF(SGRT .NE. 0) PDAY = DAY
        RDPT = C.0
        GO TO 150,
147  IF(DRSGP(DAY) .LE. 0.0) GO TO 149
    DO 148 KHOUR = 1,EHSGD
148  DRHP(DAY,KHOUR) = (WSG*DRSGP(DAY))/EHSGDF
149  IF(SGRT .NE. 0) PDAY = DAY
150  CONTINUE
    CALL DAYNXT(DAY,COPY)
    IF(DAY .EQ. 274) GO TO 151
    IF(CONOPT(8) .EQ. 0) GO TO 146
    IF(DAY .NE. SGMD) GO TO 146
    WSG = WSG2
    SGRT = SGRT2
    GO TO 145
151  MONTH = 1
    MCAY = 273
    AMRPM = 0.0
    AMPREC = 0.0
AMBF = C.0
AMSE = C.0
AMSTF = 0.0
AMRTF = 0.0
WRITE(6,3) (TITLE(KTA), KTA = 1,20)
3 FCRMAT(1H1,10X,20A4)
WRITE(6,4) (YTITLE(KTA), KTA = 1,20),YR1,YR2
4 FORMAT(1H0,20A4,2X,13HWATER YEAR 19, WRITE(6,5)
5 FCRMAT(8H OCTOBER)
C BEGIN DAY LOOP
152 TDSF = 0.0
IF(DAY.LT.151.OR.DAY.GT.265) PET = 0.35*DPET(DAY)
IF(DAY.GE.151.AND.DAY.LT.166) PET = 0.41*DPET(DAY)
IF(DAY.GE.166.AND.DAY.LT.182) PET = 0.47*DPET(DAY)
IF(DAY.GE.182.AND.DAY.LT.197) PET = 0.67*DPET(DAY)
IF(DAY.GE.197.AND.DAY.LT.228) PET = 0.80*DPET(DAY)
IF(DAY.GE.228.AND.DAY.LT.244) PET = 0.74*DPET(DAY)
IF(DAY.GE.244.AND.DAY.LT.266) PET = 0.61*DPET(DAY)
PETU = PET
TFMAX = 0.0
BMIR = BMTR
IF(DAY .LT. NDTUZ) BMIR = BMTR/GFIE
IF(CTNOPT(15) .NE. 1) GO TO 322
IF(DAY.LT.151.OR.DAY.GT.265) REDX = 1.0
IF(DAY.GE.151.AND.DAY.LT.166) REDX = 0.35/0.41
IF(DAY.GE.166.AND.DAY.LT.182) REDX = 0.35/0.47
IF(DAY.GE.182.AND.DAY.LT.197) REDX = 0.35/0.67
IF(DAY.GE.197.AND.DAY.LT.228) REDX = 0.35/0.80
IF(DAY.GE.228.AND.DAY.LT.244) REDX = 0.35/0.74
IF(DAY.GE.244.AND.DAY.LT.266) REDX = 0.35/0.61
IF(DAY .EQ. ISST1 .OR. DAY .EQ. ISST2) TSST = TSST + AISS
PWER = ALP4
IF(DAY .LT. KDAY1 .OR. DAY .GT. KDAY2) PWER = ALP4/ALP5
322 TDOSSL = 0.0
C EVAPOTRANSPIRATION ADJUSTMENTS
IF(CONOPT(7) .NE. 1) GO TO 153
IF(DMXT(DAY) - 4.0*ELDF .LT. 40.0) PET = 0.0
IF(SPTW .GT. SPTWCC) PET = FFOR*PET

C CALCULATION OF SNOW EVAPORATION

IF(DMNT(DAY) .GT. 32.0 OR SPTW .LE. DPSE(DAY)) GO TO 153
SE = DPSE(DAY)
AMSNE = AMSNE + SE
SPTW = SPTW - SE
IF(SFMD .GT. 0.0) SDEPTH = SDEPTH - SE/SFMD

153 DO 202 HOUR = 1, 24
IF((NGRD .EQ. 0) AND (DRHP(DAY, HOUR) .NE. 0.0) AND (PET .EQ. 0)) PET = 0.5*PET
1
IF(HCUR .EQ. SGRT + 1) RGPM = DRGPM(DAY)
IF(HOUR .EQ. 9) HSE = (FWTR + PET)/12.0
IF(HCUR .EQ. 21) HSE = 0.0
PRH = RGPM*DRHP(DAY, HOUR)
AMPREC = AMPREC + PRH

C ENTER SNOMEL SUBROUTINE
IF(CONOPT(7) .EQ. 1) CALL SNOMEL(BDDFSM, SPTWCC, SPM, ELDF, DAY, SPBFLW, XDNFS, FFOR, FFSI, MRNSM, DSMGH, SDEPTH, STMD, PXCSA, HOUR,
1 SAX, SORF, ORFIS, SOFRI, AMFSL, PRH, SPTW, TANSM, SPLW, SFMD, OFRF,
2 WT4AM, WT4PM, ASM, ASMRF, SASFX, SARAX, DMXT, DMNT, RICY, FIRR, TEH)
TEHCO = TEH - 4.0*ELDF
IF(TEHCO .LE. 32.0) REDX = 0.0

155 AMRPM = AMRPM + PRH
156 TOFR = 0.0
ARHF = 0.0
ARSF = 0.0
IF(CONOPT(15) .EQ. 1) TSST = TSST/EXP(PWER)

C 15 MINUTE ACCOUNTING AND ROUTING LOOP

DO 187 PRD = 1, 4
PEBI = C.0
PPI = 0.0
OFR = 0.0
OFRIS = 0.0
WI = 0.0
```
WEIFS = 0.0
PMFUZS = 0.0
PMELZS = 0.0
PMEIFS = 0.0
PMEOFs = 0.0
PEP = 0.25*PRH
IF(CONOPT(2) .EQ. 1) CALL PREPRD(RGPM,DRHP,DAY,HOUR,DPY,PRO,PEP,PRH)
1 PRH
IF(CONOPT(15) .NE. 1) GO TO 325
SPIX = (4.0*PEP)**ALP1
SSPLH = BETA1*SPIX
SSST = BETA2*REDX*SPIX
325 IF(PEP .GT. 0.0) GO TO 157
IF(OFUS .GT. 0.0) GO TO 159
IF(IF .GT. 0.0) GO TO 170
IF(INRTRI .GT. 0) GO TO 172
TRHF = 0.0
TRSF = 0.0
IF(RHFO .GT. 0.0) GO TO 181
GO TO 104
325 IF(PEP .GE. VINTCR) GO TO 158
UZS = UZS + PEP*TPLR
VINTCR = VINTCR - PEP
PPI = 0.0
PEBI = 0.0
PMEUZS = PEP
IF(OFUS .GT. 0.0) GO TO 159
GO TO 170
157 IF(PEP .GE. VINTCR) GO TO 158
UZS = UZS + PEP*TPLR
VINTCR = VINTCR - PEP
PPI = 0.0
PEBI = 0.0
PMEUZS = PEP
IF(OFUS .GT. 0.0) GO TO 159
GO TO 170
158 PPI = PEP - VINTCR
UZS = UZS + VINTCR*TPLR
VINTCR = 0.0
LZSR = LZS/LZC
UZC = SUZC*AEX90 + BUZC*EXP(-2.7*LZSR)
IF(UZC .LT. 0.25) UZC = 0.25
UZR = 2.0*ABS(UZS/UZC - 1.0) + 1.0
```
FMR = (1.0/(1.0 + UZRX))**UZRX
IF(UZS .GT. UZC) FMR = 1.0 - FMR
PEBI = PPI*FMR
PMEUZS = PEP - PEBI
UZS = UZS + PPI - PEBI

C LOWER ZCNE AND GROUNDWATER INFILTRATION
159 LZR = Lzs/Lzc
EID = 4.0*LZSR
IF(LZSR .LE. 1.0) GO TO 160
EID = 4.0 + 2.0*(LZSR - 1.0)
IF(LZSR .LE. 2.0) GO TO 160
EID = 6.0
160 PEBI = PEBI + OFUS
CMIR = C.25*SIAM*BMIR/(2.0**EID)
CIVM = EIVF*2.0**LZSR
IF(CIVM .LT. 1.0) CIVM = 1.0
PEAI = PEBI*PEBI/(2.0*CMIR*CIVM)
WI = PEBI*PEBI/(2.0*CMIR)
IF(PBI .GE. CMIR) WI = PEBI - 0.5*CMIR
IF(PBI .GE. CMIR*CIVM) PEAI = PEBI - 0.5*CMIR*CIVM
WEIFS = WI - PEAI
IF(PBI .LE. OFUS) GO TO 161
PMEZS = (PEBI - WI)*((PEBI - OFUS)/PEBI)
PMEIFS = WEIFS*((PEBI - OFUS)/PEBI)
PMEIFS = PEAI*PBI - OFUS/PEBI)
CONTINUE
161 CCNTINUE
IF((PEAI - OFUS) .GT. 0.0) GO TO 162
EQD = (CFUS + PEAI)/2.0
GO TO 163
162 EQD = ECD{((PEAI - OFUS)**0.6)
163 IF((OFUS + PEAI) .GT. (2.0*EQD)) EQD = 0.5*(OFUS + PEAI)
IF((OFUS + PEAI) .LT. 0.001) GO TO 164
OFUS = 0.25*OFRF*(((OFUS + PEAI)*0.5)**0.6)**1.67)*((1.0 + 0.6*OFUS + 1 PEAI)/(2.0*EQD)**3.0)**1.67)
IF(OFR .GT. (0.75*PEAI)) OFUS = 0.75*PEAI
164 IF(FIMP .EQ. 0.0) GO TO 168
165 PEIS = PPl + OFUSIS
IF((PEIS - OFUSIS) *GT. 0.0) GO TO 166
EQDIS = (OFUSIS + PEIS)/2.0
GO TO 167
166 EQDIS = EQDFIS*( (PEIS - OFUSIS)**0.6 )
167 IF((OFUSIS + PEIS) *GT. (2.0*EQDIS)) EQDIS = 0.5*(OFUSIS + PEIS)
IF((OFUSIS + PEIS) *LE. 0.01) GO TO 168
OFRIS = 0.25*OFRIS*(((OFUSIS + PEIS)*0.5)**1.67)*((1.0 + 0.6*((OFUSIS + PEIS)/(2.0*EQnFIS)))**3.0)**1.67
1 OFUSIS = PEIS/(2.0*EQDFIS)**3.0)**1.67
IF(OFRIS *GT. PEIS) OFRIS = PEIS
168 TOFR = TOFR + FPER*OFR + FIMP*OFRIS + PPI*FWTR
OFUSIS = PEIS - OFRIS
CFUS = PEAI - OFRIS
IF(OFUS *GE. 0.001) GO TO 169
LZS = L2S + OFUS
OFUS = 0.0
OFRIS = OFRIS + OFUSIS
OFUSIS = 0.0
169 LZRX = 1.5*ABS(LZS/LZC - 1.0) + 1.0
FMR = (1.0/(1.0 + LZRX))**LZRX
IF(LZS *LT. LZC) FMR = 1.0 - FMR*(LZS/LZC)
PLZS = FMR*(PEBI - WI)
PGW = (1.0 -FMR)*((PEBI - WI)*((1.0 - SUBWF)*FPER
GWS = GWS + PGW
BFNX = BFNX + PGW
LZS = L2S + PLZS
IFS = IFS*WEIFS*FPER
170 SPIF = IFRL*IFS
AMIF = AMIF + SPIF
IFS = IFS - SPIF
IF(IFS *GE. 0.0001) GO TO 171
LZS = L2S + IFS
IFS = 0.0
171 UHFA(1) = FPER*OFR + PPI*FWTR + FIMP*OFRIS + SPIF
SPDR = UHFA(1)
IF(CONOPT(15)*NE.1) GO TO 172
TROVQ = BETA3*SPDR**ALP2
TSST = TSST + SSTO
IF(TROVQ .GT. TSST) TROVQ = TSST
TSST = TSST - TROVQ
IF(TSST .LT. 0.0) TSST = 0.0
SCROV = BETA5*SPDR**BETA6
USFA(I) = SSPLH + TROVQ + SCROV

ROUTING
172 IF(CONOPT(12) .NE. 1) GO TO 173
URHF = URHF + 0.25*UHFA(1)
IF(CONOPT(15) .EQ. 1) URSF = URSF + 0.25*USFA(1)
IF(PRDF .NE. 4) GO TO 181
UHFA(1) = URHF
IF(CONOPT(15) .EQ. 1) USFA(1) = URSF

173 TRHF = 0.0
TRSF = 0.0
KTRI = NCTRI
IF(CONOPT(13) .EQ. 1) KTRI = NCSTRI

174 URHF = LHFA(KTRI)
IF(CONOPT(15) .EQ. 1) URSF = USFA(KTRI)
IF(URHF.LE.0.0) GO TO 176

TRHF = TRHF + URHF*CTR(KTRI)
IF(CONOPT(13) .EQ. 1 .AND. LSHFT .AND. KTRI .GE. 2) TRHF = TRHF + MAIN0523
1 URHF*SATRI(KTRI - 1)
UHFA(KTRI + 1) = URHF
IF(CONOPT(15) .EQ. 1) TRSF = TRSF + URSF*CTR(KTRI)
IF(CONOPT(13) .EQ. 1 .AND. LSHFT .AND. KTRI .GE. 2 .AND. CONOPT(15 .EQ. 1) TRSF = TRSF + URSF*SATRI(KTRI - 1)
IF(CONOPT(15) .EQ. 1) USFA(KTRI + 1) = URSF

C
C PROGRAM ASSUMES THAT WHEN TRHF = 0.0 THEN TRSF = 0.0
GO TO 177
176 UHFA(KTRI+ 1) = 0.0
IF(CONOPT(15) .EQ. 1) USFA(KTRI + 1) = 0.0
177 KTRI = KTRI - 1
IF(KTRI .GE. 1) GO TO 174
178 IF(URHF .LE. 0.0) GO TO 179
NRTRI = NCTRI
IF(CONOPT(13) .EQ. 1) NRTRI = MXTRI
179 NRTRI = NRTRI - 1
UHFA(1) = 0.0
USFA(1) = 0.0
IF(CONOPT(13) .NE. 1) GO TO 180
NNSTRI = NCTRI + 1
UHFA(NNSTRI) = 0.0
USFA(NNSTRI) = 0.0
180 URHF = 0.0
URSF = 0.0
181 IF(SRX .LE. CSRX) SRX = CSRX
RHF1 = TRHF - SRX*(TRHF - RHFO)
RHFO = RHFI
IF(CONOPT(15) .EQ. 1) RSDF1 = TRSF - SRX*(TRSF - RSDFO)
IF(CONOPT(15) .EQ. 1) RSDFO = RSDF1
IF(RHFO .LT. RHFMC) RHFO = 0.0
TFCFS = (4.0*RHF1 + CBF - HSE)*WCFS
IF(CONOPT(13) .NE. 1) GO TO 182
IF(CONOPT(12) .EQ. 1 .AND. PRO .NE. 4) GO TO 182
CALL RTVARY (CTRI, SATRI, BTRI, CHCAP, NBTRI, MXTRI, NCSTRI, EXQPV, LSHFT)
1 TFCFS
DATE = MOD(DAY, MCAY)
IF(LSHFT) WRITE(6,6) DATE, HOUR, PRD, NCSTRI
6 FORMAT(2X,I2,2X,I2,2X,I2,2X,20HIST0GRAM CHANGES TO,IX,12,IX,18HELEMENTS)
182 CONTINUE
IF(TFCFS .LE. 0.5*CHCAP) SRX = CSRX
IF((TFCFS .GT. 0.5*CHCAP) .AND. (TFCFS .LT. 2.0*CHCAP)) SRX = CSRX
1 *(FSRX - CSRX)*((TFCFS - 0.5*CHCAP)/(1.5*CHCAP))**3
IF(TFCFS .GT. 2.0*CHCAP) SRX = FSRX
IF(TFCFS .LE. TFMAX) GO TO 183
PRDF = PRD
TDFP24 = HOUR
IF(PRDF .LE. 3) TDFP24 = (TDFP24 - 1.0) + 0.15*PRDF
TFMAX = TFCFS
183 ARHF = ARHF + RHF1
    IF(CONOPT(15) .EQ. 1) ARSF = ARSF + RSDF1
C STORM OUTPUT REQUESTED BY CONOPT(1)
184 IF(CONOPT(1) .NE. 1) GO TO 186
    IF(DAY .NE. CDSDR) GO TO 186
    IF(HOUR .EQ. 1 .AND. PRD .EQ. 1) WRITE(16,7)
7 FORMAT(1H/,21X,19HRAINFALL DEPOSITION,12X,16HMOISTURE STORAGE,
1 14X,17HSTREAMFLOW ORIGIN,6X,14HSTREAM OUTFLOW/2X,11HDDY HR PD RAMAIN0581
2IN EUZS ELZS EIFS EOFS UZS LZS IFS OFS SMAIN0582
3POF SPF SPBF SPTF INCHES CFS)
    GATE = MOD(DAY,MCAY)
    CFS = OFUS*FPER + OFUSIS*FIMP
    SPOF = 0.25*(CBF-HSE)
    SPTF = SPOR + SPBF
    SPDR = 0.0
    IF(RHFO .LE. 0.0) TFCFS = (CBF - HSE)*WCFS
    RSPTF = 0.25*TFCFS/WCFS
    WRITE(16,8) DATE,HOUR,PRDPEP,PMEUZS,PMEIFS,PMELZS,PMEIFS,PMEOFSPZS,LUZS,LZS
8 FORMAT(2X,12,1X,11,5X,F6.4,2X,4(F7.4),2X,5(1X,F6.4),IX 1 F7.1)
    IF(HOUR .EQ. 24 .AND. PRD .EQ. 4) GO TO 185
    GO TO 166
185 NDSDP = NDSDP + 1
    IF(NDSFR .EQ. NDSDP) GO TO 186
    CALL CAYNXT(CDSOR,DY)
186 CONTINUE
    IF(VINTCR .LT. 0.25*VINTMR) VINTCR = VINTCR + DPET(DAY)/96.0
    CONTINUE
187 CONTINUE
C END OF 15 MINUTE LOOP
    IF(CONOPT(5) .NE. 1) GO TO 197
C HOURLY OVERLAND FLOW AND RAINFALL SORTING
    IF(TOFR .LE. 0.0) GO TO 193
    KT20 = 20
188 IF(KT20 .LT. 1) GO TO 192
    IF(TOFR .GT. T200FH(KT20)) GO TO 189
GO TO 190
189 T200FH(KT20+1) = T200FH(KT20)
   GO TC 191
190 T200FH(KT20+1) = TOFR
   GO TO 193
191 KT20 = KT20 - 1
   GO TO 188
192 T200FH(1) = TOFR
193 IF(PRH .LE. O.C) GO TO 197
   KT20 = 20
194 IF(KT20 .LT. 1) GO TO 196
   T20PRH(KT20 + 1) = PRH
   IF(PRH .GT. T20PRH(KT20)) GO TO 195
   GO TO 197
195 T20PRH(KT20+1) = T20PRH(KT20)
   KT20 = KT20 - 1
   GO TO 194
196 T20PRH(1) = PRH
C ADDING GROUNDWATER FLOW
197 CBF = GWS*BFRL*(1.0 + BFNRL*BFNX)
   GWS = GWS - CBF
   AMBF = AMBF + CBF
   THGR = ARHF + CBF
   IF(HSE .GT. THGR) HSE = THGR
   AMSE = AMSE + HSE
   IF(CONOPT(15) .EQ. 1) TSSF(HOUR) = ARS
   THSF(HOUR) = (THGR - HSE)*WCFS
   TDSF = TDSF + THSF(HOUR)
   IF(CONOPT(15) .EQ. 1) TDSSL = TDSSL + TSSF(HOUR)
C DRAINING OF UPPER ZONE STORAGE
198 UZINFX = (UZS/UZC) - (LZS/LZC)
   IF(UZINFX .LE. 0.0) GO TO 198
   LZSR = LZS/LZC
   UZINLZ = 0.003*BMR*UZC*UZINFX**3.0
   IF(UZINLZ .GT. UZS) UZINLZ = UZS
   UZS = UZS - UZINLZ
LZRX = 1.5*ABS(LZSR - 1.0) + 1.0

FMR = (1.0/(1.0 + LZRX))*LZRX

IF(LZS .LT. LZC) FMR = 1.0 - FMR*LZSR

PGW = (1.0-FMR)*UZILNZ*(1.0 - SUBWF)*FPER

PLZS = FMR*UZILNZ

LZS = LZS + PLZS

GWS = GWS + PGW

BFNX = BFNX + PGW

C 4 PM ADJUSTMENTS OF VARIOUS VALUES

198 IF(HOUR .NE. 16) GO TO 202

AEX90 = 0.9*(AEX90 + PET)

AEX96 = 0.96*(AEX96 + PET)

C INFILTRATION CORRECTION

SIAM = (AEX96/AETX)**SIAC

IF(SIAM .LT. 0.33) SIAM = 0.33

BFNX = 0.97*BFNX

IF(PET .EQ. 0.0) GO TO 202

C EVAP-TRANS LOSS FROM GROUNDWATER

GWET = GWS*GWETF*PET*FPER

GWS = GWS - GWET

BFNX = BFNX - GWET

IF(BFNX .LT. 0.0) BFNX = 0.0

AMPET = AMPET + PET

IF(PET .GE. UZS) GO TO 199

UZS = UZS - PET

AMNET = AMNET + PET

GO TO 202

199 PET = PET - UZS

AMNET = AMNET + UZS

UZS = 0.0

LZSR = LZS/LZC

IF(PET .GE. ETLF*LZSR) GO TO 200

SET = PET*(1.0 - PET/(2.0*ETLF*LZSR))

GO TO 201

200 SET = 0.5*ETLF*LZSR

201 LZS = LZS - SET
AMNET = AMNET + SET

202 CONTINUE

C END OF HOUR LOOP

DSSF(DAY) = TDSF/24.0
IF(CONOPT(11) .EQ. 1) DSSF(DAY) = DSSF(DAY) + DDIW(DAY)
IF(CONOPT(15) .NE. 1) GO TO 203
DSSE(DAY) = TDSSL
SCOUR(DAY) = BETA4*DRSF(DAY)**ALP3
DSSL(DAY) = SCCUR(DAY) + DSSE(DAY)

203 AMRTF = AMRTF + CRSF(DAY)
AMSTF = AMSTF + CSSF(DAY)
IF(CONOPT(6) .EQ. 1) EDLZS(DAY) = L zs

C STORE ERRORS AND FLOW DURATION

IF(CONOPT(4) .NE. 1) GO TO 204
ERR = DSSF(DAY) - DRSF(DAY)
IF(DRSF(DAY) .LT. 1.0) KRFMI = 1.0
IF(DRSF(DAY) .GT. 1.0) KRFMI = 2.0*ALOG(DRSF(DAY)) + 2.0
CRFMI(KRFMI) = CRFMI(KRFMI) + 1.0
SERR(KRFMI) = SERR(KRFMI) + ERR
SERA(KRFMI) = SERA(KRFMI) + ABS(ERR)
SQER(KRFMI) = SQER(KRFMI) + ERR*ERR
SESF(KRFMI) = 0.0
IF(CRFMI(KRFMI) .GT. 1.0) SESF(KRFMI) = SQRT(ABS((SQER(KRFMI) -
1 SERR(KRFMI)**2/CRFMI(KRFMI))/(CRFMI(KRFMI) - 1.0)))

204 IF(DAY .EQ. 366) MDAY = 337
DATE = MOD(DAY, MDAY)
IF(TFMAX .LE. RMPF) GO TO 206
WRITE(6,9) DATE, (THSF(HOUR), HOUR=1,12)
FORMAT(1H/,1X/,1X,14,2X,2HAM,1X,6F8.1,3X,6F8.1)
WRITE(6,10) (TSSF(HOUR), HOUR=13,24), DSSF(DAY)
10 FORMAT(1HJ,6X,2HPM,1X,6F8.1,3X,7F8.1)
IF(TDFP24 .LT. 12.0) GO TO 205
TDFP12 = TDFP24 - 12.0
WRITE(6,11) TFMAX, TDFP12
11 FORMAT(1H/,10X,8HMAXIMUM=,F8.1,2X,6HC.F.S.,5X,4HTIME,3X,F5.2,2X,
1 4HP.M.)
GO TO 206
205 WRITE(6,12) TFMAX,TDFP24
12 FORMAT(I1H,10X,8HMAXIMUM=,F8.1,2X,6HC.F.S.,5X,4HTIME,3X,F5.2,2X,4HA.M.)
206 IF(CONOPT(7) .EQ. 1 .AND. SDEP .GT. 0.0) WRITE(6,13)DATE
13 FORMAT(I4,2X,7HSTMD=,F7.2,2X,4HTANSM=,F6.2,2X,4HSPLW=,F6.2)

MONTHLY SUMMARY STORAGE
IF(DAY .NE. MEDWY(MONTH)) GO TO 220
TMSTF(MONTH) = AMSTF
AMSTF = 0.0
TMRTF(MONTH) = AMRTF
AMRTF = 0.0
EMBFNX(MONTH) = BFNX
TMPREC(MONTH) = AMPREC
AMPREC = 0.0
TMRF(MONTH) = AMRF
AMRF = 0.0
TMBF(MONTH) = AMBF
AMB = 0.0
TMIF(MONTH) = AMIF
AMIF = 0.0
TMSE(MONTH) = AMSE
AMSE = 0.0
TMPET(MONTH) = AMPET
AMPET = 0.0
TMNET(MONTH) = AMNET
AMNET = 0.0
TMSENE(MONTH) = AMSN
AMSNE = 0.0
TMFSIL(MONTH) = AMFSIL
AMFSIL = 0.0
EMGW(S(MONTH) = GWS
UZC = SUZC*AEXSO + BUZC*EXP(-2.7*LZS/LZC)
IF(UZC .LT. 0.25) UZC = 0.25
EMUZC(MCNTN) = UZC
EMUZS(MCNTN) = UZS
EMSIAM(MCNTN) = SIAM
EMLZS(MCNTN) = LZS
EMIFS(MCNTN) = IFS
IF(MONTH .EQ. 5) MEDWY(5) = 59
MAY = MEDWY(MCNTN)
207 IF(MONTH .NE. 0) GO TO (208,209,210,211,212,213,214,215,216,217,218,219), MONTH
208 WRITE(6,14)
14 FORMAT(1H/,8HNOVEMBER)
GO TO 219
209 WRITE(6,15)
15 FORMAT(1H/,8HDECEMBER)
GO TO 219
210 WRITE(6,16)
16 FORMAT(1H/,7HJANUARY)
GO TO 219
211 WRITE(6,17)
17 FORMAT(1H/,8HFEBRUARY)
GO TO 219
212 WRITE(6,18)
18 FORMAT(1H/,5HMARCH)
GO TO 219
213 WRITE(6,19)
19 FORMAT(1H/,5HAPRIL)
GO TO 219
214 WRITE(6,20)
20 FORMAT(1H/,3HMAY)
GO TO 219
215 WRITE(6,21)
21 FORMAT(1H/,4HJUNE)
GO TO 219
216 WRITE(6,22)
22 FORMAT(1H/,4HJULY)
GO TO 219
217 WRITE(6,23)
23 FORMAT(1H/,6HAUGUST)
   GO TO 219
218 WRITE(6,24)
24 FORMAT(1H/,9HSEPTEMBER)
219 MONTH = MONTH + 1
220 CALL DAYNXT(DAY,DPY)
   IF(DAY .NE. 274) GO TO 152
C END OF DAY LOOP
221 CONTINUE
222 WRITE(6,25) (TITLE(KTA), KTA=1,20,1)
25 FORMAT(1H1,10X,20A4)
   WRITE(6,26) (YTITLE(KTA),KTA=1,15,1),YR1,YR2
26 FORMAT(1H/,15A4,3X,14HWATER YEAR 19,12,1H-,12,7X,
           1 29H KENTUCKY WATERSHED MODEL)
C ANNUAL SUMMARY
   SATFV = 0.0
   RATFV = 0.0
   APREC = 0.0
   ABFV = 0.0
   ARPM = 0.0
   ASEV = 0.0
   ANET = 0.0
   APET = 0.0
   AIFV = 0.0
   ASE = 0.0
   AFSIL = 0.0
   DO 223 MONTH = 1,12
      SATFV = SATFV + TMSTF(MONTH)
      RATFV = RATFV + TMRTF(MONTH)
      APREC = APREC + TMPREC(MONTH)
      ABFV = ABFV + TMBF(MONTH)
      ARPM = ARPM + TMRPM(MONTH)
      ASEV = ASEV + TMSE(MONTH)
      ANET = ANET + TMNET(MONTH)
      APET = APET + TMPET(MONTH)
   END
AIFV = AIFV + TMIF(MONTH)
ASE = ASE + TMSN(MONTH)
223 AFSIL = AFSIL + TMFSIL(MONTH)
IF(CONOPT(14) .NE. 1) GO TO 224
WRITE(6,27)
27 FCRMAT(1H///44X,20HRECORDED FLOWS)
CALL DAYOUT(DRF,MEDWY,DPY)
WRITE(6,28)
28 FCRMAT(1H///44X,23HSYNTHETIC FLOWS)
224 CALL DAYOUT(DSSF,MEDWY,DPY)
WRITE(6,29) (TMSTF(KWD), KWD=1,12), SATFV
DO 225 MONTH = 1,12
225 TMSTFI(MONTH) = (TMSTF(MONTH) - TMIF(MONTH) - TM8F(MONTH) - TMSE(MONTH) +
AOFV = SATFV - AIFV - ABFV + ASEV
IF(AOVF .LT. 0.0) AOFV = 0.0
WRITE(6,31) (TMOF(KWD), KWD=1,12), AOFV
31 FCRMAT(1X,9HOVERLAND,5X,12F8.3,4X,F7.3,2X,6HINCHES)
WRITE(6,32) (TMIFKWD), KWD=1,12), AIFV
32 FCRMAT(1X,9HINTERFLOW,4X,12F8.3,4X,F7.3,2X,6HINCHES)
WRITE(6,33) (THBF(KWD), KWD=1,12), ABFV
33 FFORMAT(IX,4HBASE,9X,12F8.3,4X,F7.3,2X,6HINCHES)
WRITE(6,34) (THBF(KWD), KWD=1,12), ASEV
34 FFORMAT(IX,9HSTREAM,1X,12F8.3,4X,F7.3,2X,6HINCHES)
IF(CONOPT(9) .EQ. 0) GO TO 227
WRITE(6,35) (TMRTF(KWD), KWD=1,12), RATFV
35 FCRMAT(1X,8HRECORDED,4X,12F8.1,2X,F10.1,2X,3HSFD)
RATFV = RATFV/VWIN
WRITE(6,36) RATFV
36 FORMAT(112X,F9.2,2X,6HINCHES)
227 WRITE(6,37) (TMPREC(KWD), KWD=1,12),APREC
37 FORMAT(1X,6HPRECIP,7X,12F8.2,3X,F8.2,2X,6HINCHES)
   IF(CONOPT(7) .EQ.1) WRITE(6,38) (TMPRM(KWD), KWD=1,12),APRM
38 FORMAT(1X,9HRAIN+MELT,4X,12F8.2,3X,F8.2,2X,6HINCHES)
   IF(CONOPT(7) .EQ.1) WRITE(6,39) (TMSNE(KWD), KWD=1,12),ASE
39 FORMAT(1X,11HSURSNOWEVAP,3X,12F8.2,3X,F7.3,2X,6HINCHES)
   IF(CONOPT(7) .EQ.1) WRITE(6,40) (TMFSIL(KWD), KWD=1,12),AFSIL
40 FORMAT(1X,11HINTSNOWLOSS,3X,12F8.2,3X,F7.3,2X,6HINCHES)
   WRITE(6,41) (TMNET(KWD), KWD=1,12),ANET
41 FORMAT(1X,12HEVP/TRAN-NET,2X,12F8.3,3X,F7.3,2X,6HINCHES)
   IF(CONOPT(7) .NE. 1) SPM = 1.0
42 FORMAT(1X,10H-POTENTIAL,2X,12F8.3,3X,F7.3,2X,6HINCHES)
43 FORMAT(1X,12HSTORAGES-UZS,2X,12F8.3,12F8.3,12X,6HINCHES)
   WRITE(6,44) (EMLZS(KWD), KWD=1,12)
44 FORMAT(1X,3HLZS,2X,12F8.3,12X,6HINCHES)
   WRITE(6,45) (EMIFS(KWD), KWD=1,12)
45 FORMAT(1X,3HIFS,2X,12F8.3,12X,6HINCHES)
   WRITE(6,46) (EMGWS(KWD), KWD=1,12)
46 FORMAT(1X,3HGWS,2X,12F8.3,12X,6HINCHES)
47 FORMAT(1X,12HINDICES-UZC,2X,12F8.3)
   WRITE(6,48) (EMBFNX(KWD), KWD=1,12)
48 FORMAT(9X,4HBFX,2X,12F8.3)
   WRITE(6,49) (EMPSIAM(KWD), KWD=1,12)
49 FORMAT(9X,4HSIAM,2X,12F8.3)
42 IF(CONOPT(7) .EQ.1) WRITE(6,50) AMBER
   AMBER = (LZS - BYLZS + IFS - BYIFS)*FPER + (UZS - BYUZS + GWS -
   BYGWS)*(1.0 - FWTR) + SATFV/VMIN + ANET*FPER + ASEV - APREC
42   2 + ASE + AFSIL - (1*SPM - 1.0)/SPM)*ASM
   WRITE(6,50) AMBER
50 FORMAT(1/7HBALANCE,5X,F10.4,2X,6HINCHES)
   IF(CONOPT(7) .EQ.1) GO TO 228
   WRITE(6,51) ASM, ASMRG
51 FORMAT(1/13HCHECK ON SNOW,5X,F10.4,5X,F10.4)
ASM = 0.0
ASMRG = 0.0

228 CONTINUE
   IF(CONOPT(4) .NE. 1) GO TO 232
   WRITE(6,52)
52 FORMAT('IC0N0PT(4), FLOW DURATION AND ERROR TABLE')
   WRITE(6,53)
53 FORMAT('FLOW INTERVAL,5X,5HCASES,3X,8HAV. ERROR,3X,'\$ 16H AVR. ABS. ERROR,3X,14HSTANDARD ERROR')
   SSESF = 0.0
   SSERA = 0.0
   SSERR = 0.0
   ACRFMI = 0.0
   DO 230 KRFMI = 1,22
     IF(KRFMI .EQ. 1) ETIBF = 0.0
     IF(KRFMI .EQ. 2) ETIBF = 1.0
     FKRFMI = KRFMI
     IF(KRFMI .GT. 2) ETIBF = EXP((FKRFMI/2.0) - 1.0)
     CCRFMI = CCRFMI(KRFMI)
     IF(CCRFMI .EQ. 0.0) WRITE(6,54) ETIBF, CCRFMI
54 FORMAT('ETIBF,CCRFMI,SERRV,SERAV')
     IF(CCRFMI .NE. 0) WRITE(6,54) ETIBF, CCRFMI, SERRV, SERAV
     SERAV = SERA(KRFMI)/CCRFMI
     SERRV = SERR(KRFMI)/CCRFMI
     IF(CCRFMI .EQ. 0.0) GO TO 229
     IF(CCRFMI .NE. 0) WRITE(6,54) ETIBF, CCRFMI, SERRV, SERAV
     1SESF(KRFMI)
229  ACRFMI = ACRFMI + CCRFMI(KRFMI)
   IF(ACRFMI .EQ. 0.0) GO TO 230
   SSERR = SSERR + SERR(KRFMI)
   SERRV = SERR/ACRFMI
   SSERA = SSERA + SERA(KRFMI)
   SSERAV = SSERAV/ACRFMI
230  SSESF = SSESF + SESF(KRFMI)
   WRITE(6,55) ACRFMI, SSERRV, SSERAV, SSESF
55 FORMAT('ACRFMI,SSERRV,SSERAV,SSESF')
FDPY = CPY
SADF = SATFV/FCPY
RADF = RATFV/FCPY
RA1 = 0.0
RA2 = 0.0
RA3 = 0.0
DO 231 CAY = 1,DPY
DRAF = CRSF(DAY) - RADF
DSAF = DSSF(DAY) - SADF
RA1 = RA1 + DRAF*DRAF
RA2 = RA2 + CSAF*DSAF
RA3 = RA3 + DRAF*DSAF
DFCC = RA3/SQRT(RA1*RA2)
WRITE(6,56) DFCC
56 FORMAT(1H/,10X,31HCORRELATION COEFFICIENT (DAILY),3X,F10.4)
232 CONTINUE
IF(ConOpt(5) .NE. 1) GO TO 233
C OUTPUT MAXIMUM RUNOFF, PRECIPITATION AT END OF YEARS
WRITE(6,57)
57 FORMAT(1H/,10X,58HTWENTY HIGHEST CLOCKHOUR RAINFALL EVENTS IN THE MAIN0953
1WATER YEAR)
WRITE(6,58) (T20PRH(KT20), KT20=1,20)
58 FORMAT(1H/,5X,20F6.3)
WRITE(6,59)
59 FORMAT(1H/,10X,70HTWENTY HIGHEST CLOCKHOUR OVERLAND FLOW RUNOFF EVENTS IN THE MAIN0958
1WATER YEAR)
WRITE(6,58) (T20OFH(KT20), KT20=1,20)
233 CONTINUE
IF(ConOpt(6) .EQ. 0) GO TO 234
WRITE(6,99)
99 FORMAT(1H1,30X,27HDAILY SOIL MOISTURE OUTPUT )
CALL DAYOUT(EDLZS,MEDWY,DPY)
WRITE(6,350)
350 FORMAT(1H1,35X,32HDAILY SHEET EROSION LOSS IN TONS//)
CALL DAYOUT(DSS, MEDW, DPY)
WRITE(6,352)
352 FORMAT(1H1,37X,27HDAILY CHANNEL SCOUR IN TONS//)
CALL DYCUT(SCUR, MEDW, DPY)
WRITE(6,354)
354 FORMAT(1H1,32X,39HCSALY SYNTHESIZED SEDIMENT LOAD IN TONS//)
CALL DOUT(DSSL, MEDW, DPY)
IF(CONOPT16).NE.1) GO TO 399
WRITE(6,356)
356 FORMAT(1H1,33X,36HDAILY RECORDED SEDIMENT LOAD IN TONS//)
CALL DOUT(DRSL, MEDW, DPY)
357 RATSV = 0.0
SATSV = 0.0
DO 236 CAY = 1,DPY
RATSV = RATSV + DRSHDAY)
236 SATSV = SATSV + DSSHDAY)
FDNY = CPY
RSX1 = C.0
RSX2 = 0.0
RSX3 = C.0
RADS = RATSV/FPDNY
SADSLS = SATSV/FPDNY
DO 238 CAY = 1,DPY
DRSL = DRSL(DAY) - RADS
DSASL = DSSL(DPY) - SADS
RSX1 = RSX1 + DRSL*DRSL
RSX2 = RSX2 + CSASL*DSASL
238 RSX3 = RSX3 + DRSL*DSASL
DSCC = RSX3/ SQRT(RSX1*RSX2)
WRITE(6,240) DSCC
240 FORMAT(1H1/,10X,33H0RRELATION COEFFICIENT(DAILY),3X,F10.4)
399 IF(NYSC.LE.NYSC) GO TO 400
IF(CONOPT10).NE.1) GO TO 100
GO TO 117
400 STOP
END
SUBROUTINE DAYNXT

SUBROUTINE DAYNXT(DAY, DPY)

DETERMINES NUMBER OF NEXT DAY OF THE YEAR

INTEGER DAY, DPY

DAY = DAY + 1
IF(DAY .EQ. 366) DAY = 1
IF(DAY .EQ. 60 .AND. DPY .EQ. 366) DAY = 366
RETURN
END

SLBROUTINE DAYCUT

SUBROUTINE DAYCUT(VDCY, MEDWY, DPY)

PRINTS TABLE OF DAILY VALUES

DIMENSION MEDWY(12), VDCY(366), VDMD(12)

INTEGER DATE, CAY, DPY

100 WRITE(6,1)
   1 FORMAT(7X,3HDAY,7X,3HOCT,5X,3HNOV,5X,3HDEC,5X,3HJAN,5X,3HFEB,5X,  
   1 3HMAR,5X,3HAPR,5X,3HMAY,5X,3HJUN,5X,3HJUL,5X,3HAUG,5X,4HSEPT)

   MEDWY(3) = 0
   DO 104 CATE = 1, 28, 1
     IF(MOD(CATE, 5) .NE. 1) GO TO 102
     DO 101 KMC = 1, 12
       CAY = MEDWY(KMC) + DATE
       VDMD(KMC) = VDCY(DAY)
       WRITE(6,2) DATE, VDMD(KMC), KMC
       2 FORMAT(1H0, 3X, I6, 3X, 1ZF8.1)
     GO TO 104
   102 DO 103 KMC = 1, 12
     DAY = MEDWY(KMC) + DATE
   103 VDMD(KMC) = VDCY(DAY)
SUBROUTINE PREPRD

SUBROUTINE PREPRD(RGPM,ORHP,DAY,HOUR,DPY,PRD,PEP,PRH)

DIVIDES HOURLY PRECIPITATION TOTALS AMONG PERIODS FOR SMALL BASINS

DIMENSION ORHP(366,24), PE4P(4)
INTEGER DAY,DPY,HOUR,PRD
PEP = 0.0
IF(PRH .EQ. 0.0) RETURN
IF(PRDP .EQ. 1) GO TO 100

WRITE(6,3) DATE,VDMD(12),(VDMD(KWD), KWD = 1,11)
3 FORMAT(1X,3X,16,3X,12F8.1)
104 CONTINUE
IF(DPY .NE. 366) GO TO 106
DATE = 29
VDCY(60) = VDCY(366)
DO 105 KMC = 1,12
DAY = MEDWY(KMC) + DATE
105 VOMO(KMC) = VDCY(60)
WRITE(6,3) DATE,VOMO(12),(VOMO(KMC), KMC=1,11)
GO TO 107
106 CONTINUE
WRITE(6,4) VDCY(302),VDCY(333),VDCY(363),VDCY(29),VDCY(88),
1VDCY(119),VDCY(149),VDCY(180),VDCY(210),VDCY(241),VDCY(272)
4 FORMAT(1X,7X,2F29,3X,4F8.1,8X,7F8.1)
107 CONTINUE
WRITE(6,5) VDCY(303),VDCY(334),VDCY(364),VDCY(30),VDCY(89),
1VDCY(120),VDCY(150),VDCY(181),VDCY(211),VDCY(242),VDCY(273)
5 FORMAT(1X,7X,2F30,3X,4F8.1,8X,7F8.1)
WRITE(6,6) VDCY(304),VDCY(365),VDCY(31),VDCY(90),VDCY(151),
1VDCY(212),VDCY(243)
6 FORMAT(1H/,7X,2H31,3X,F8.1,8X,F8.1,8X,F8.1,8X,F8.1,8X,F8.1,8X,F8.1,8X,F8.1)
MEDWY(3) = 365
RETURN
END

C
C
C SUBROUTINE PREPRD

C SUBROUTINE PREPRD(RGPM,DRHP,DAY,HOUR,DPY,PRD,PEP,PRH)
C DIVIDES HOURLY PRECIPITATION TOTALS AMONG PERIODS FOR SMALL BASINS
C DIMENSION DRHP(366,24), PE4P(4)
C INTEGER DAY,DPY,HOUR,PRD
C PEP = 0.0
C IF(PRHP .EQ. 0.0) RETURN
C IF(PRDP .EQ. 1) GO TO 100

C
PEP = PE4P(PRD)
RETURN

100 LHOUR = HOUR - 1
LCAY = CAY
IF(LHOUR .GE. 1) GO TO 101
LHOUR = 24
LCAY = CAY - 1
IF(LCAY .EQ. 0) LDAY = 365
IF(LCAY .EQ. 365) LDAY = 59
IF(LDAY .EQ. 59 .AND. DPY .EQ. 366) LDAY = 366

101 PRLH = RGPM*DRHP(LCAY, LHOUR)
NHOUR = HOUR + 1
NCAY = CAY
IF(NHOUR .LE. 24) GO TO 102
NHOUR = 1
CALL CAYNXT(NDAY, DPY)

102 PRNH = RGPM*DRHP(NDAY, NHOUR)
IF(PRH .GT. PRLH .AND. PRH .GT. PRNH) GO TO 103
GO TO 104

103 PE4P(1) = 0.10
PE4P(2) = 0.28
PE4P(3) = 0.46
PE4P(4) = 0.16
GO TO 108

104 IF(PRH .LT. PRLH .AND. PRH .LT. PRNH) GO TO 105
GO TO 106

105 PE4P(1) = 0.28
PE4P(2) = 0.10
PE4P(3) = 0.16
PE4P(4) = 0.46
GO TO 108

106 IF(PRNH .GE. PRLH) GO TO 107
PE4P(1) = 0.46
PE4P(2) = 0.16
PE4P(3) = 0.28
PE4P(4) = 0.10
GO TO 108
107 PE4P(1) = 0.10
PE4P(2) = 0.28
PE4P(3) = 0.16
PE4P(4) = 0.46
108 DO 109 KPRD = 1,4
109 PE4P(KPRD) = PE4P(KPRD)*PRH
PEP = PE4P(1)
RETURN
END

C C C C
SUBROUTINE RTVARY
SUBROUTINE RTVARY(CTRI, SATRI, BTRI, CHCAP, NBTRI, MXTRI, NCTRI, EXQPV, LSHFT, TFCFS)
DIMENSION AWSBIT(99), BTRI(99), CTRI(99), SATRI(99)
LOGICAL LSHFT
DO 100 KIA = 1, MXTRI
Satri(KIA) = 0.0
AWSBIT(KIA) = 0.0
LSHFT = .FALSE.
FMXTRI = MXTRI
FNbTRI = NBTRI
FNpTRI = NCTRI
TFX = TFCFS
TFMRT = 0.1*CHCAP
IF(TFX .LT. TFMRT) TFX = TFMRT
IF((FNpTRI .EQ. FMXTRI .AND. TFX .EQ. TFMRT) RETURN
FNTRI = FNBTRI*(CHCAP/TFX)**EXQPV + 0.5
IF(FNTRI .LT. 1.0) FNTRI = 1.01
NCTRI = FNTRI
FNSTRI = NCTRI
IF(FNSTRI .NE. FNpTRI) LSHFT = .TRUE.
IF(.NOT. LSHFT) RETURN
IF(FNPNTRI  .GT. 98.5) GO TO 101
FCNTRI = ABS(FNSTRI - FNPNTRI)
IF(FCNTRI  .LE. 1.1) GO TO 101
IF(FNSTRI  .GT. FNPNTRI) FNSTRI = FNPNTRI + 1.0
IF(FNSTRI  .LT. FNPNTRI) FNSTRI = FNPNTRI - 1.0
NCTRI = FNSTRI
101 KB1 = 0
KB2 = 1
KB3 = 0
102 KB1 = KB1 + 1
IF(KB1  .GT. NBTRI) GO TO 105
KB4 = 0
WSBIT = TRKKB(KB1)/FNSTRI
103 KB4 = KB4 + 1
IF(KB4  .GT. NCTRI) GO TO 102
AWSBIT(KB2) = AWSBIT(KB2) + WSBIT
KB3 = KB3 + 1
IF(KB3  .LT. NBTRI) GO TO 104
KB3 = 0
KB2 = KB2 + 1
104 GO TO 103
105 IF(FNPNTRI  .GT. 98.5) GO TO 108
DO 107 KB6 = 1,NCTRI
DO 106 KB7 = 1,KB6
106 SATRI(KB6) = SATRI(KB6) + AWSBIT(KB7) - CTRI(KB7)
107 CONTINUE
108 DC 109 KB5 = 1,MXTRI
109 CTRI(KB5) = AWSBIT(KB5)
RETURN
END

C
SUBROUTINE SNOWEL
SUBROUTINE SNOMEL,BDDFSM,SPTWCC,SPM,ELDIF,DAY,SPBFLW,XDNFS,FFOR, SNOW0001
SNOWMELT COMPUTATION

DIMENSION DMNT(366),DMXT(366),FIRR(15),RICY(366)
INTEGER DAYfHCUR
REAL HhSMfMRNSM

IF((CAY .NE. 274) .OR. (HOUR .NE. D) GO TO 100
SPLW = 0.0
XELR = C.0
SDSC = C.0278
FDSC = C.0
FTA = 0.0
RICO = 0.0
KRIA = C

100 CONTINUE

CALCULATION OF HOURLY AIR TEMPERATURE

C DMXT CURRENT DAY, DMNT NEXT DAY
IF(HOUR .NE. 4) GO TO 101
FDSC = C.0
FTA = FDSC
WT4PM = DMXT(DAY) - 4.0*ELDIF + (XELR/4.0)*0.7*ELDIF

101 IF(HOUR .EQ. 10) SDSC = -0.0278
IF(HOUR .EQ. 22) SDSC = 0.0278
IF(HOUR .EQ. 16) GO TO 102
NDAY = 1
IF(NDAY .EQ. 366) NDAY = 1
IF(NDAY .EQ. 60 .AND. DMXT(366) .NE. 0.0) NDAY = 366
IF(NCAY .EQ. 367) NDAY = 60
WT4AM = DMNT(NCAY) - (XELR/4.0)*3.3*ELDIF

102 IF(IPRH .LE. 0.0 .OR. XELR .GE. 4.0) GO TO 103
WT4AM = WT4AM - 0.825*ELDIF
WT4PM = WT4PM + 0.175*ELDIF
XELR = XELR + 1.0

103 IF(IPRH .NE. 0.0 .OR. XELR .LE. 0.0) GO TO 104
WT4AM = WT4AM + 0.825*ELDIF
\[ \text{WT4PM} = \text{WT4PM} - 0.175 \times \text{ELDIF} \]
\[ \text{XELR} = \text{XELR} - 1.0 \]
\[ 104 \text{ TEH} = \text{WT4AM} + \text{FTA} \times (\text{WT4PM} - \text{WT4AM}) \]
\[ \text{FOSC} = \text{FOSC} + \text{SDSC} \]
\[ \text{FTA} = \text{FTA} + \text{FOSC} \]
\[ \text{IF}(\text{PRH} + \text{SPTW} \cdot \text{EQ.} \cdot 0.0) \text{ GO TO 128} \]
\[ \text{IF}(\text{HOUR} \cdot \text{NE.} \cdot 24) \text{ GO TO 105} \]
\[ \text{CALCULATION OF TIME AGING OF THE SNOWPACK} \]
\[ \text{SAX} = \text{SAX} + 1.0 \]
\[ \text{IF}(\text{SAX} \cdot \text{GT.} \cdot 15.0) \text{ SAX} = 15.0 \]
\[ 105 \text{ IF}(\text{TEH} \cdot \text{GT.} \cdot 32.0) \text{ GO TO 110} \]
\[ \text{PRECIPITATION IN FORM OF SNOW - CALCULATE INTERCEPTION DENSITY OF NEWSNOW} \]
\[ \text{SNCW COMPACTION, AND SETTLING SNOW PACK AND THE EFFECT ON ALBEDO} \]
\[ \text{IF}(\text{PRH} \cdot \text{LE.} \cdot 0.0) \text{ GO TO 110} \]
\[ \text{PRH} = \text{SF} \times \text{PRH} \]
\[ \text{HSE} = \text{PRH} \]
\[ \text{ASM} = \text{ASM} + \text{HSE} \]
\[ \text{PRH} = (1.0 - (\text{FFSI} \times \text{FOR})) \times \text{PRH} \]
\[ \text{HSFRG} = \text{PRH} \]
\[ \text{ASM} = \text{ASM} + \text{HSFRG} \]
\[ \text{FSIL} = \text{FFSI} \times \text{FOR} \times \text{HSE} \]
\[ \text{AMFSIL} = \text{AMFSIL} + \text{FSIL} \]
\[ \text{IF}(\text{TEH} \cdot \text{LE.} \cdot 0.0) \text{ GO TO 106} \]
\[ \text{DNFS} = \text{XDNFS} + ((0.01 \times \text{TEH}) \times 2) \]
\[ \text{GO TO 107} \]
\[ 106 \text{ DNFS} = \text{XDNFS} \]
\[ 107 \text{ IF}(\text{SPTW} \cdot \text{GT.} \cdot 0.0 \cdot \text{AND.} \cdot \text{SDEPHT} \cdot \text{GT.} \cdot \text{SPTW}) \text{ SDEPHT} = \text{SDEPHT} - \{(\text{PRH} \times \text{SDEPHT}) \times (0.10 \times \text{SDEPHT}) \times 0.25) \}
\[ \text{SPTW} = \text{SPTW} + \text{PRH} \]
\[ \text{SDEPHT} = \text{SDEPHT} + (\text{PRH} \div \text{DNFS}) \]
\[ \text{SASFX} = \text{SASFX} + \text{PRH} \]
\[ \text{IF}(\text{SASFX} \cdot \text{GE.} \cdot \text{PXCSA}) \text{ GO TO 108} \]
\[ \text{GO TO 109} \]
\[ 108 \text{ SAX} = \text{SAX} - 1.0 \]
\[ \text{IF}(\text{SAX} \cdot \text{LT.} \cdot 0.0) \text{ SAX} = 0.0 \]
\[ \text{SASFX} = \text{SASFX} - \text{PXCSA} \]
109 PRH = 0.0
110 CONTINUE
   IF(SPTV .LE. 0.0) GO TO 127
C SEASONAL MELT FACTOR ADJUSTMENT
C PROGRAM MODIFICATION
   KA0 = KRIA
C PROGRAM MODIFICATION
   RICD = RICY(DAY)
   IF(TEH .LE. 32.0) GO TO 111
   GO TO 114
C CALCULATION OF NEGATIVE MELT
111 IF(TANSM .LE. 11.5*MRNSM) GO TO 112
   IF(TANSM .LT. 1.0) TANSM = TANSM + ((5.0*MRNSM)**(1.3 + 2.0*  
     0.08*SPTU)
   TANSM = 0.08*SPTW
   GO TO 115
112 TANSM = TANSM + MRNSM
113 IF(TANSM .GT. 0.08*SPTW) TANSM = 0.08*SPTW
   GO TO 127
C EFFECT OF RAIN ON ALBEDO
114 SARAX = SARAX + PRH
   IF(SARAX .LT. PXCSA/2.0) GO TO 115
   SAX = SAX + 1.0
   IF(SAX .LT. 15.0) SAX = 15.0
   SASFX = 0.0
   SARAX = SARAX - (PXCSA/2.0)
115 IF(TEH .GT. 32.0) HSM = (TEH - 32.0)*BDDFSM
   IF(TEH .LT. 32.0) HSM = 0.0
   HSM = HSM*RICO
   KAA = 1.0 + SAX
   IF(SAX .LT. 15.0) HSM = HSM*(1.0 - ((1.0 - FFOR)*FIRR(KAA)))
   IF(SAX .EQ. 15.0) HSM = HSM*(1.0 - ((1.0 - FFOR)*FIRR(15)))
   IF(PRH .GT. 0.0) HSM = HSM + ((TEH - 32.0)*PRH/144.0))
   IF(STMD .GT. 0.3 .AND. SPTW .LT. SPTWCC) GO TO 116
   GO TO 117
116 MHSM = HSM
   HSM = (SPTW/SPTWCC)*HSM
IF(HSM .LT. 0.1*MHSM) HSM = 0.1*MHSM
117 IF(HSM .LT. SPTW) GO TO 118
    HSM = SPTW
    SDEPTH = 0.0
    SPTW = 0.0
    SPLW = 0.0
    RICO = 0.0
    TANSM = 0.0
    SAX = 15.0
    OFRF = OFRF
    OFRFIS = OFRFIS
    GO TO 122
118 SPTW = SPTW - HSM
    IF(SFMD .LE. 0.0) GO TO 122
    IF(SAX .GE. 15.0) GO TO 121
    IF(SAX .GE. 6.0) GO TO 119
    SDEPTH = SDEPTH - (HSM/(0.5*SFMD))
    GO TO 122
119 IF(SAX .LT. 10.0) GO TO 120
    SDEPTH = SDEPTH - (HSM/(0.9*SFMD))
    GO TO 122
120 SDEPTH = SDEPTH - (HSM/(0.7*SFMD))
    GO TO 122
121 SDEPTH = SDEPTH - (HSM/SFMD)
122 CONTINUE
    IF(SPTW .LT. 0.00001) SPTW = 0.0
C CALCULATION OF LIQUID-WATER-HOLDING CAPACITY
    SPLWC = SPBFLW*SPTW
    IF(SFMD .GT. 0.6) SPLWC = SPBFLW*(3.0 - 3.33*SFMD)*SPTW
    IF(SPLWC .LT. 0.0) SPLWC = 0.0
C ACCOUNTING OF MELT WATER AND RAIN
    IF((SPLW + HSM + PRH) .GT. (SPLWC + TANSM)) GO TO 123
    GO TO 124
123 PRH = HSM + PRH + SPLW - SPLWC - TANSM
    SPLW = SPLWC
    SPTW = SPTW + TANSM
TANSM = 0.0
GO TO 127
124 IF((HSM + PRH) .LE. TANSM) GO TO 126
125 SPTW = SPTW + TANSM
SPLW = SPLW + HSM + PRH - TANSM
PRH = 0.0
TANSM = 0.0
GO TO 127
126 TANSM = TANSM - HSM - PRH
SPTW = SPTW + HSM + PRH
PRH = 0.0
127 CONTINUE
HSM = 0.0
C CALCULATION OF DENSITY AND ADJUSTMENT OF OVERLAND FLOW TIME
IF(SDEPTH .LE. 0.0 .OR. SPTW .GE. SDEPTH) GO TO 128
STMD = (SPTW + SPLW)/SDEPTH
SFMD = SPTW/SDEPTH
OFRF = 0.33*SOFRF
IF(SPTW .LE. SPTWCC) OFRF = (1.0 - (SPTW/SPTWCC)*0.67)*SOFRF
128 IF(SDEPTH .LE. 0.0) OFRF = SOFRF
OFRFIS = SOFRFI*OFRF/SOFRF
C CALCULATION OF GROUNDMELT
IF(HOUR .NE. 12 .OR. SPTW .LE. 0.0) RETURN
IF(SPTW .LE. DSMGH) GO TO 129
PRH = PRH + DSMGH
SPTW = SPTW - DSMGH
IF(STMD .LT. 0.50 .AND. SDEPTH .GT. 2.0*DSMGH) SDEPTH = SDEPTH -
1 2.0*DSMGH
RETURN
129 PRH = SPTW + PRH + SPLW
TANSM = 0.0
RICD = C.0
SPLW = C.0
SDEPTH = C.0
SPTW = C.0
SAX = 15.0
OFRF = SOFRF
OFRFIS = SOFRFI
RETURN
END
APPENDIX B. CONTROL OPTIONS FOR PROGRAM
LISTING ON APPENDIX A
CONTRCL OPTIONS FOR PROGRAM LISTING ON APPENDIX A

<table>
<thead>
<tr>
<th>OPTION</th>
<th>VALUE</th>
<th>DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>IF 15-MINUTE STORM DETAILS ARE REQUESTED.</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>IF RAIN IS NOT TO BE DIVIDED EQUALLY AMONG 15-MINUTE PERIODS.</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>IF EVAPORATION IS TO BE READ BY 10-DAY PERIODS. DAILY EVAPORATION DATA ARE READ OTHERWISE.</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>IF A DAILY FLOW ERROR TABLE IS REQUESTED. THIS OPTION CANNOT BE USED IF OPTION 9 IS NOT IN EFFECT.</td>
</tr>
<tr>
<td>5</td>
<td>1</td>
<td>IF THE TOP TWENTY HOURLY RAINFALLS AND OVERLAND FLOWS ARE REQUESTED.</td>
</tr>
<tr>
<td>6</td>
<td>1</td>
<td>IF DAILY SOIL MOISTURE STORAGE VALUES ARE REQUESTED.</td>
</tr>
<tr>
<td>7</td>
<td>1</td>
<td>IF SNOW IS TO BE INCLUDED IN THE ANALYSIS.</td>
</tr>
<tr>
<td>8</td>
<td>1</td>
<td>IF THE RAINFALL STORAGE GAGE SITE IS MOVED DURING THE WATER YEAR.</td>
</tr>
<tr>
<td>9</td>
<td>1</td>
<td>IF DAILY RECORDED STREAMFLOWS ARE TO BE READ.</td>
</tr>
<tr>
<td>10</td>
<td>1</td>
<td>IF NEXT YEAR OF DATA REQUIRES READING NEW PARAMETERS. THIS IS NORMALLY USED WHEN TWO WATERSHEDS ARE SYNTHESIZED IN THE SAME RUN.</td>
</tr>
<tr>
<td>11</td>
<td>1</td>
<td>IF STREAMFLOW DIVERSIONS ARE TO BE READ.</td>
</tr>
<tr>
<td>12</td>
<td>1</td>
<td>IF STREAM ROUTING IS TO BE DONE HOURLY. ROUTING IS DONE ON A 15-MINUTE INCREMENT OTHERWISE.</td>
</tr>
</tbody>
</table>
13 1 IF THE LENGTH OF THE TIME-AREA HISTOGRAM IS TO BE VARIED WITH FLOW.

14 1 IF THE RECORDED STREAMFLOWS ARE TO BE PRINTED.

15 1 IF THE SHEET EROSION MODEL IS TO BE INCLUDED IN THE ANALYSIS. THIS OPTION CANNOT BE USED IF OPTION 9 IS NOT IN EFFECT.

16 1 IF RECORDED SUSPENDED LOADS ARE TO BE READ FOR COMPARISON WITH SYNTHESIZED SUSPENDED LOADS. THIS OPTION CANNOT BE USED IF OPTIONS 9 AND 15 ARE NOT IN EFFECT.
APPENDIX C. SAMPLE INPUT DATA FOR PROGRAM LISTING ON APPENDIX A
INPUT DATA FOR WATERSHED AND SHEET EROSION MODELS
FOR
FOUR MILE CREEK NEAR TRAER, IOWA. 1970 WATER YEAR

27

0.0094 0.0231 0.0288 0.0202 0.0239 0.0283 0.0373 0.0370 0.0502 0.0587
0.0373 0.0344 0.0442 0.0540 0.0460 0.0513 0.0536 0.0613 0.0434 0.0367
0.0300 0.0373 0.0352 0.0296 0.0128
0.76 0.75 0.74 0.73 0.72 0.71 0.70 0.69 0.68 0.66 0.64 0.62 0.60 0.58 0.56
0.000
0.000
0.000
0.000
0.000
0.000
0.000
0.000
0.000
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0.100
0.100
0.100
0.100
0.005
0.005
0.005
0.005
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<th>FCLR Mile Creek Area Near Traer, Iowa - Water Year 1969-1970</th>
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</tr>
</tbody>
</table>

- **0.32 0.31 0.31 0.30 0.31 0.31 0.29 0.27**
| 24.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 11.0 | 1.0 | 5.0 | -6.0 | -12.0 | -18.0 | -15.0 | -18.0 | -17.0 | -14.0 | 3.0 | -1.0 | -9.0 | -9.0 |
| 12.0 | -3.0 | -20.0 | -22.0 | -26.0 | -26.0 | 0.0 | 0.0 | 19.0 | 22.0 | 18.0 | 17.0 | 14.0 | 8.0 |
| 8.0 | 20.0 | -9.0 | -14.0 | -14.0 | 10.0 | 11.0 | 23.0 | 25.0 | 22.0 | 20.0 | 23.0 | 5.0 | -1.0 | -1.0 |
| 2.0 | 2.0 | 7.0 | 27.0 | -3.0 | -2.0 | -1.0 | 24.0 | 20.0 | 23.0 | 7.0 | 7.0 | 17.0 | 18.0 | 19.0 |
| 33.0 | 35.0 | 13.0 | 24.0 | 27.0 | 28.0 | 27.0 | 22.0 | 21.0 | 21.0 | 19.0 | 14.0 | 16.0 | 14.0 | 14.0 |
| 18.0 | 24.0 | 28.0 | 31.0 | 20.0 | 21.0 | 27.0 | 22.0 | 29.0 | 23.0 | 15.0 | 4.0 | 15.0 | 23.0 | 24.0 |
| 26.0 | 21.0 | 23.0 | 26.0 | 31.0 | 34.0 | 31.0 | 43.0 | 31.0 | 24.0 | 26.0 | 37.0 | 39.0 | 36.0 | 41.0 |
| 34.0 | 34.0 | 38.0 | 40.0 | 36.0 | 34.0 | 32.0 | 36.0 | 44.0 | 50.0 | 57.0 | 60.0 | 61.0 | 51.0 |
| 37.0 | 37.0 | 37.0 | 36.0 | 29.0 | 32.0 | 34.0 | 34.0 | 35.0 | 40.0 | 35.0 | 24.0 | 26.0 | 12.0 | 12.0 |
| 20.0 | 21.0 | 26.0 | 13.0 | 10.0 | 11.0 | 18.0 | 25.0 | 26.0 | 28.0 | 18.0 | 25.0 | 12.0 | 20.0 | 20.0 |
| 27.0 | 26.0 | 26.0 | 10.0 | 10.0 | 26.0 | 28.0 | 17.0 | 12.0 | 16.0 | 5.0 | 6.0 | 21.0 | 17.0 | 4.0 |
| -1.0 | 5.0 | 26.0 | 14.0 | 14.0 | 5.0 | 6.0 | 10.0 | -5.0 | 12.0 | 4.0 | -5.0 | 6.0 | 17.0 | 10.0 |
| 13.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |

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69 10 5 2       0.03
69 10 6 1 0.05 0.05
69 10 10 2       0.01 0.01 0.03
69 10 11 1 0.04 0.06
69 10 12 1       0.05 0.10 0.10 0.02 0.03 0.03
69 10 12 2 0.04 0.03 0.05 0.05 0.03 0.02 0.01 0.03 0.01 0.02 0.07 0.03
69 10 13 1 0.18 0.03
69 10 15 2       0.01 0.03 0.01 0.04
69 10 16 1 0.05 0.01
69 10 19 1 0.03 0.07 0.21 0.09 0.03 0.02 0.05 0.14
69 10 19 2       0.01 0.04
69 10 30 1       0.01 0.03 0.08 0.06
69 10 30 2 0.08 0.06 0.03 0.01 0.01 0.03 0.06 0.02 0.06 0.11 0.12 0.03
69 10 31 1 0.02 0.04 0.01       0.01
69 11 3 1       0.01 0.01 0.01 0.01
69 11 3 2       0.01 0.01
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69 12 6 1       0.02
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APPENDIX D. STREAMFLOW SIMULATION RESULTS FOR FOUR MILE CREEK WATERSHED NEAR TRAER, IOWA
Table D-1. Daily recorded and simulated streamflows for the Four Mile Creek watershed near Traer, Iowa for the 1970 water year

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APPENDIX E. SEDIMENT SIMULATION RESULTS FOR FOUR MILE CREEK WATERSHED NEAR TRAER, IOWA
Table E-1. Daily recorded and simulated suspended sediment loads for the Four Mile Creek watershed near Traer, Iowa for the 1970 water year

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Total

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Table E-2. Daily recorded and simulated suspended sediment loads for the Four Mile Creek
Traer, Iowa for the 1971 water year

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Total: 997.64 931.10 5478.80 2764.40 99.14 108.90 542.14 395.30
Table E-2 (Continued)

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| Total | 401.70 | 733.60 | 925.37 | 448.70 | 10.91 | 19.90 | 4.67 | 39.70 |