A LUMPED, DETERMINISTIC RAINFALL-RUNOFF MODEL FOR SMALL, FORESTED WATERSHEDS IN SOUTHEASTERN OKLAHOMA

By

RONALD JOSEPH McCORMICK

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Michigan Technological University

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Thesis Approved:

Thomas B. Lynch
Thesis Adviser

Norman N. Durham
Dean of the Graduate College

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TABLE OF CONTENTS

Chapter Page

Chapter Page

LIST OF TABLES

LIST OF FIGURES

Figure Page

CHAPTER I

INTRODUCTION

Linsley (1981), in a review article, reported that the first known quantitative relationship between rainfall and streamflow was described by Perreault in 1674. While many fundamental properties of stormflow production were discovered in the following years, the first comprehensive attempts at modeling this complex system of interrelated processes did not occur until the 1950's, with the advent of the digital computer.

With this increase in available computing power, hydrologists could use longer and more detailed series of equations with larger data sets, and still compute outputs relatively quickly. By 1960 both the United States Army Corp of Engineers and Stanford University had developed predictive models for large catchments, whose later adaptations are still in use today (Fleming,1975).

With the increase in intensive forest management practices in southeastern Oklahoma there has been an increase in concern about the effects these practices could have on water quality and quantity. Oklahoma State University is cooperating with the Weyerhaeuser Company, the Nekoosa Paper Company, and the Oklahoma Division of Forestry in a long term research project to study these effects. Five years of pretreatment precipitation and stormflow data have been collected for three small watersheds in S.E. Oklahoma. Several analyses were proposed for this baseline data.

One analysis proposed for this study was to develop a model to predict stormflow from a forested watershed in response to rainfall. Such a model would have to: 1) be simple to understand and operate, 2) need only available or easily obtainable data, and 3) accurately predict stormflow volumes and peaks. Initial use of the model would be to quantify changes in peak flow rates and total flow volumes due to silvicultural practices by predicting stormflow from post-treatment storms and comparing those predicted values to the observed stormflow values. Future additions to the model might include sediment and nutrient transport subsystems.

The specific objectives of this project are:

1. To organize the five years of pretreatment rainfall and stormflow data into a useable form for this project and future modeling efforts.
2. To develop a simple, lumped, deterministic stormflow prediction model using one year of the baseline rainfall and stormflow information from one watershed.
3. To verify the model, using a separate year of baseline data.

CHAPTER II

LITERATURE REVIEW

Stormflow Generation

Stormflow pathways on a forested watershed are complex and varied. Physical factors affecting stormflow include soil texture, structure, and depth, geology, topography, and vegetation. Understanding the interaction of these factors in the production of stormflow is a necessary first step in modeling stormflow generation.

Variable Source Area Concept

Since the early 1960's the Variable Source Area Concept has been the dominant theory in describing stormflow generation on forested watersheds (Betson, 1964; Hewlett and Hibbert, 1976). The underlying principle of this theory is that the infiltration capacity of an unsaturated soil on a forested watershed is rarely exceeded by rainfall intensity (Kirby and Chorley,1976). Surface runoff is therefore not an important consideration in the generation of stormflow on forested watersheds. Stormflow is generated from four other sources: baseflow, direct channel interception, subsurface saturated flow, and surface flow over saturated areas (Hewlett and Troendle, 1975).

Baseflow is streamflow resulting from the groundwater table intersecting the land surface at the channel. Baseflow comprises most of the water in a channel between rainfall and snowfall events for intermittent and perennial streams. Baseflow is greatly reduced in these types of streams during a precipitation event due to an increase in the depth of water in the stream increasing the hydraulic head, forcing baseflow back into the streambank (Satterlund, 1972). Ephemeral streams are generally above the local groundwater table and thus have little or no baseflow component.

Direct channel interception is precipitation falling on the stream surface or onto saturated areas near the stream channel. While usually amounting to only one or two percent of total stormflow, channel interception can increase as the saturated areas around the streams increase. This is because rain falling on a saturated area is, in essence, falling on a water surface and is quickly converted to stormflow. As the storm continues the saturated areas increase in size and thus intercept more precipitation directly, increasing the amount of channel interception (Hewlett, 1982).

Subsurface saturated flow and saturated overland flow, or return flow, are the primary sources of stormflow on forested watersheds. When enough precipitation occurs on the watershed, the soil water retention capacity (field capacity) is filled, then subsurface detention storage is filled (soil moisture above field capacity). This water in detention storage can move downslope, beneath the ground surface, with gravity.

When subsurface flow reaches the saturated area near the channel, part may emerge as return flow. As precipitation continues, the saturated area near the channel expands, producing a larger area that can contribute return flow. Since the area is saturated an increase in direct precipitation onto water surfaces occurs, and thus precipitation is converted to stormflow at a greater and increasing rate (Sloan et al., 1983).

Modeling

Mathematical modeling can be defined as the representation of physical processes with mathematical equations. That is, reducing a naturally complex process such as the generation of flow on a watershed to an orderly set of equations, or submodels (Hewlett and Troendle, 1975). Hundreds of hydrologic models are in use today, ranging from simple to complex in data requirements, daily to yearly in time interval, and that can simulate stormflow from large urbanized areas to small, forested watersheds. Thus, the first step in any modeling effort is to determine which modeling concept best suits the study area.

Model Classification

Two major types of mathematical models have been used by hydrologists: stochastic and deterministic. Stochastic models incorporate some type of random function, usually static precipitation input calculated from historical data. Given the same initial conditions, a stochastic model will not always produce the same results. Deterministic models are non-random, or, for any given set of initial conditions the model will produce the same output (Riley and Hawkins, 1975). The above classifications can be further divided into lumped or distributed models. Lumped models assume that the catchment characteristics are uniform over the entire area. Distributed models try to represent areal variation on the watershed by dividing the area into smaller, separate elements. These separate areas produce stormflow that then "flows" into an adjacent down-slope element, and eventually to an element bordering the stream channel (Fleming, 1975).

Classifying a model lets the reader or potential user know something about the model characteristics by identifying some of the assumptions underlying that particular model. As stated in the objectives of this project, a simple, lumped, deterministic model is to be developed for small forested watersheds in southeastern Oklahoma. The model is to be simple in the sense of requiring few data inputs, data either already available or easily obtained. It is lumped in the sense that inputs and physical processes are assumed uniform over the entire watershed area (i.e. no variation in time or space). It is deterministic in that the model is non-random, physically based, and given the same initial conditions and inputs, will produce the same output for every trial (Clarke, 1973; Linsley, 1981). The model is named the Clayton, Oklahoma Watershed model, and is hereafter referred to as the Clayton modeling project. Three existing models were considered as a basis for the Clayton model's development.

Hydrologic Models

Shih, Hawkins, and Chambers Model

Shih, Hawkins, and Chambers (1972) developed a lumped, deterministic stormflow model (Shih-Hawkins) on small forested watersheds in central Oregon. The model structure is based on generally accepted stormflow production theory for forested watersheds and thus has no surface runoff component (Fleming, 1975). The general structure of the model is presented in Figure 1. Daily precipitation, temperature, and humidity are used as inputs to the model. When

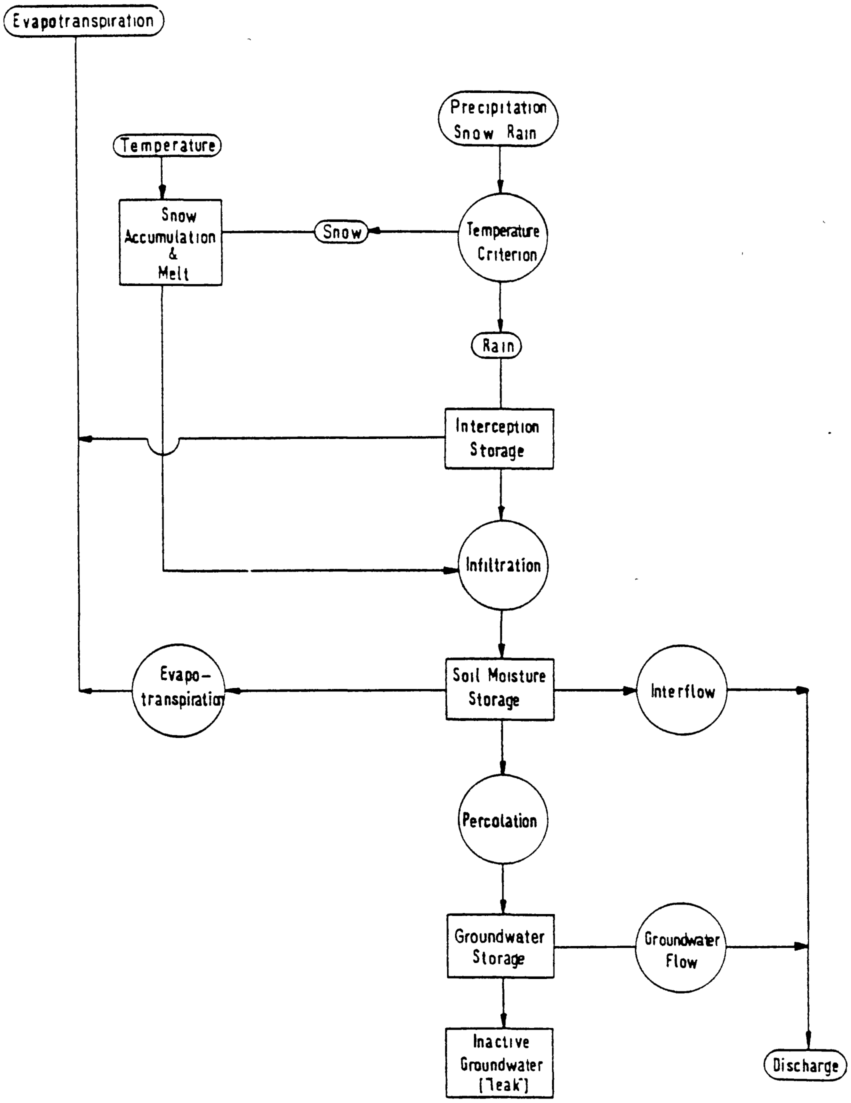


Figure 1. Structure of the Shih, Hawkins, and Chambers Model

precipitation occurs, vegetative interception storage is filled and any excess precipitation becomes throughfall. A percentage of the throughfall is input to the channel, becomes stormflow, and the balance is infiltrated into the soil. A portion of any snow present is melted and infiltrated. The cycle is initiated again the following day.

Since the parameters are lumped, the model can be thought of as a small "tank" of soil. Precipitation enters the soil by infiltration and fills the soil moisture storage, that is, fills the tank retention capacity. Some water is percolated deeper into the soil and appears later as groundwater flow (or baseflow). Any moisture in excess of retention storage or deep seepage to groundwater becomes interflow (saturated subsurface flow) and eventually is discharged as stormflow. The model outputs daily water yield as a sum of the channel interception, interflow, and groundwater flow.

Leaf and Brink Model

The Leaf-Brink model was developed for mountain watersheds in Colorado (Leaf and Brink, 1973). It is conceptually very similar to the soil tank model of Shih, Hawkins and Chambers. The two differ in type of dominant precipitation. Snow comprises the majority of precipitation input to the Leaf-Brink model, whereas rainfall dominates the Shih-Hawkins model. The Leaf-Brink model uses the same physical processes of stormflow generation as Shih-Hawkins, and thus all snowmelt infiltrates the soil. Stormflow is generated in much the same way as in the Shih-Hawkins model. The general structure for the Leaf-Brink model is shown in Figure 2.

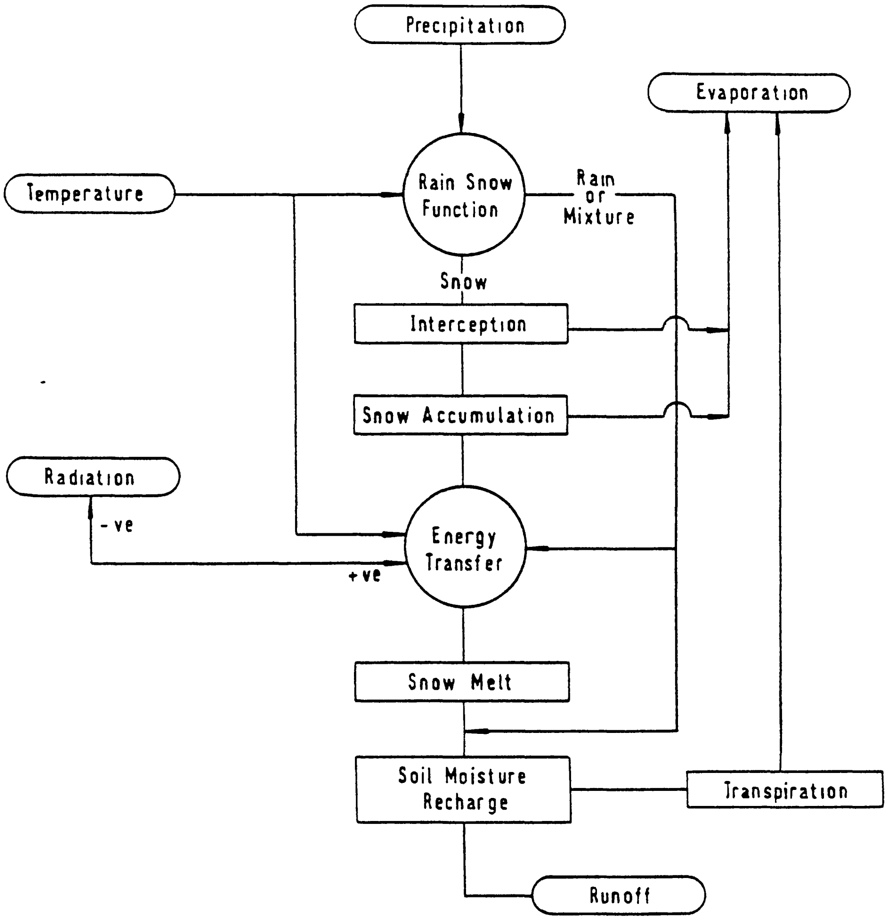


Figure 2. Structure of the Leaf and Brink Model

Kentucky Appalachian Daily Watershed Model

The Kentucky Appalachian Daily Watershed model (Kentucky), developed by Sloan et al. (1983), incorporates the Variable Source Area Concept to expand or shrink the size of the soil tank producing stormflow. The general structure of the Kentucky model is shown in Figure 3. There are 3 main stormflow producing subsystems: direct channel interception incorporating a variable source (saturated) area near the channel, subsurface flow (interflow), and groundwater flow (baseflow).

After interception storage is filled, a percentage of throughfall becomes stormflow from channel interception and the variable source area. This saturated portion of the watershed expands or contracts exponentially in response to an increase or decrease in moisture in the Soil Zone. The water infiltrating into the Soil Zone (Figure 3) is either converted to interflow or allowed to percolate into the Groundwater Zone. Interflow increases exponentially as soil moisture inputs continue. If no precipitation is occurring the Soil Zone is depleted by evapotranspiration.

Water in the Groundwater Zone is either converted to baseflow or lost from the watershed to deep seepage. Although a Groundwater Zone is included, the Kentucky model was verified on the Little Millseat watershed, a watershed with no baseflow component, thus the Groundwater Zone portion of the model was not tested or verified in the reported trial of the model.

Rogerson's Soil Moisture Balance Model

Rogerson (1976) developed a model to predict soil moisture balances

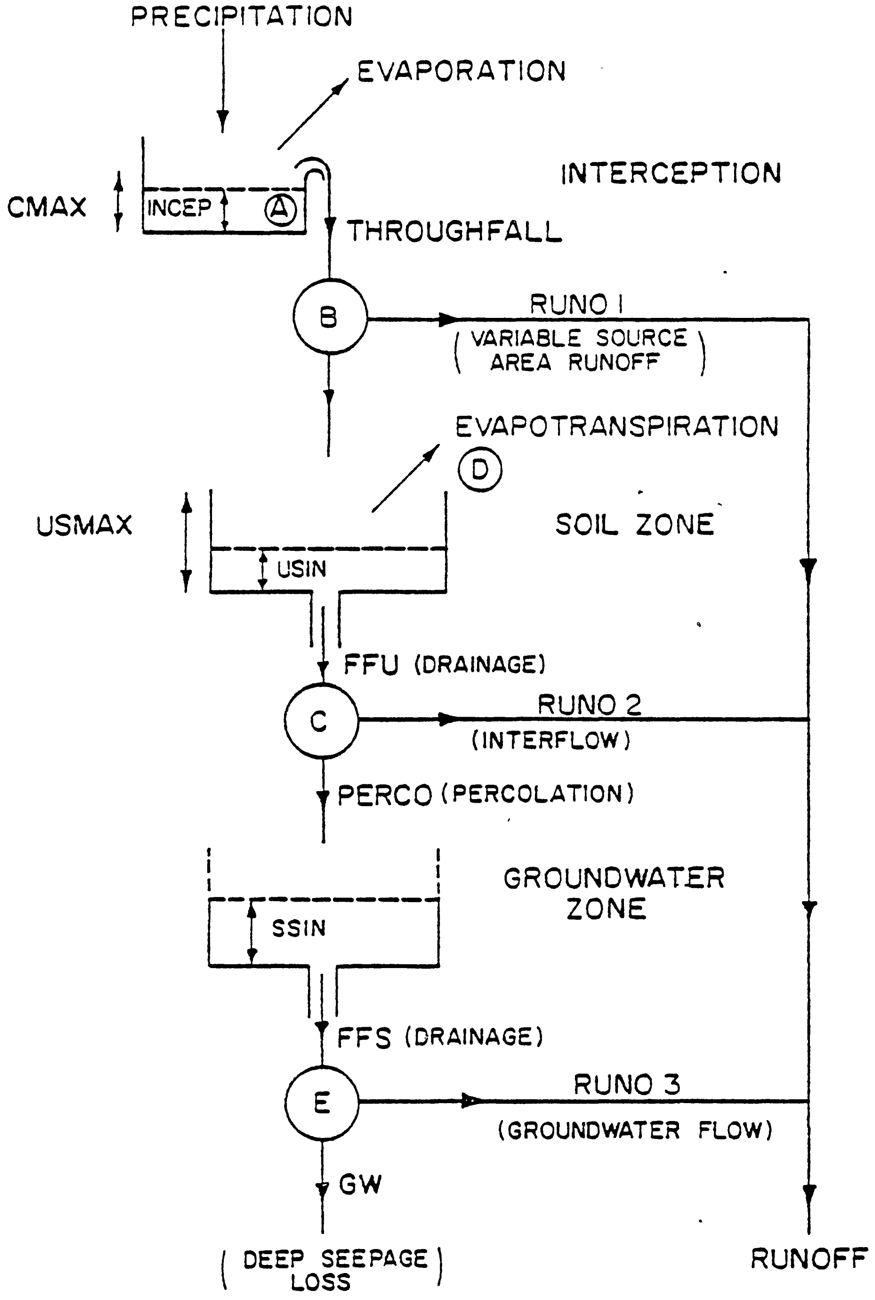


Figure 3. Structure of the Kentucky Watershed Model

on a daily basis. This model can operate stochastically (randomly) with random inputs of precipitation, or use actual precipitation data from a site. The basic structure follows the soil tank model of stormflow production. The model was developed for the Ouachita Mountains of Arkansas, an area with soils, climate, and vegetation similar to the area associated with the watersheds being studied in southeastern Oklahoma. Relationships developed by Rogerson to determine soil moisture content of a soil can be directly incorporated into the Clayton model to generate daily available soil moisture values needed as inputs.

CHAPTER III

METHODS AND MATERIALS

Study Site

Three experimental watersheds were located and established in the Kiamichi Mountains near Clayton, Oklahoma in 1978. One of these watersheds was considered in this study and is hereafter referred to as Watershed I. Watershed I is approximately 8.4 hectares (20.8 acres) in size, with an elevation of 418 meters (1370 feet) above sea level. It has an average slope of 14 percent with a northwest aspect. Figure 4 shows the shape and drainage pattern of Watershed I. The major soil series on the watershed is the Octavia stony fine sandy loam (Fine-loamy, siliceous, thermic Typic Paleudult). The Carnasaw stony loam (Clayey, mixed, thermic Typic Hapludult) is present in the upper regions of the watershed, occupying less steeply sloped areas. Octavia soils are well drained with an 18 inch sandy loam colluvium over clay loam and clay subsurface horizons. Average depth of the entire solum is 60 inches. The Carnasaw soil is a deep soil weathered from shale and sandstone, with a shallow (seven inches) sandy loam over clay. Total solum thickness is from 40 to 60 inches (Bain and Waterson, 1979).

Average annual precipitation in the study area from 1978 to 1983 was 40 inches. Dominant vegetation on the watershed was shortleaf pine (Pinus echinata), with a mixed hardwood understory. The watershed had been free of silvicultural operations for about 20 years prior to the

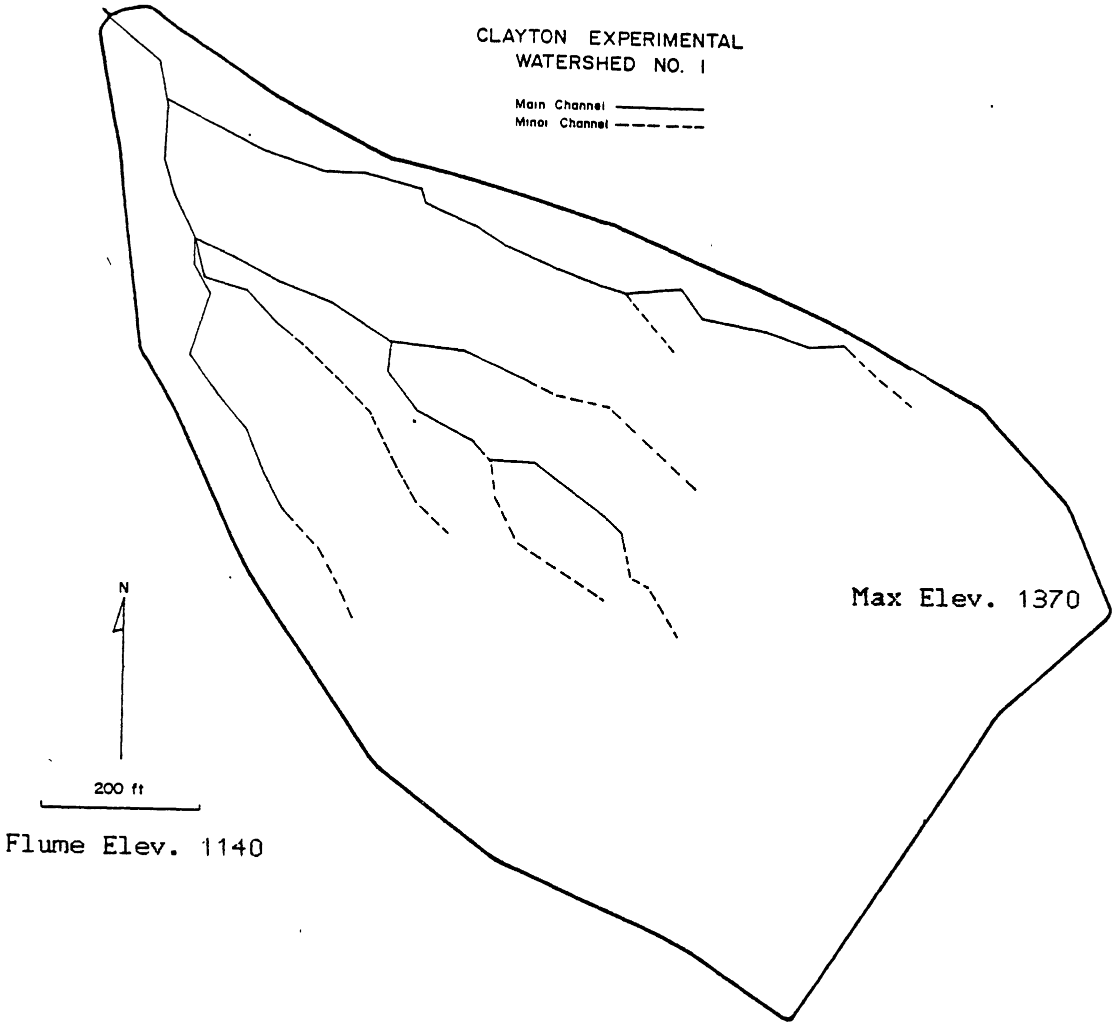


Figure 4. Shape and Drainage Pattern of Watershed I

initiation of this study. Pretreatment precipitation, stream discharge, and water quality data were collected from 1978 through 1983. Watershed I was clearcut in the spring of 1984.

Data

Five years of precipitation and stream discharge data had been collected from Watershed I prior to harvesting. Stream stage charts of observed stormflow were reduced to individual data points consisting of a date, time, and discharge value. Each datum represented a small, straight line segment of the stormflow hydrograph. Precipitation charts from a recording rain gauge were reduced to data points consisting of a date, time, and total depth of rainfall up to that point.

A computer program was developed to segment this data into 15 minute intervals. Precipitation intensity was calculated as inches per 15 minutes for each fifteen minute period. Discharge data was in cubic feet per second. Each precipitation amount had a corresponding discharge value calculated for each time interval. Data for four years was thus segmented, excluding the 1978-79 water year due to gaps in the discharge data.

As the model was to be used on a rainfall event basis, a duration period for each storm was determined. The criteria used for storm duration calculation was the time of precipitation from start to end plus an additional 24 hours. If any additional precipitation occurred in the 24 hour period after the end of a precipitation period it was added to the initial rainfall amount and the next 24 hour interval was checked for precipitation. Using this criteria the four years of precipitation data was divided into 145 separate storms. These 145 storms were stratified into five groups by total precipitation depth (Table I).

TABLE I

STORM SIZE DISTRIBUTION

Total Precipitation Depth (inches)	Number of storms Calibration	Verification
<0.5	45	23
0.5-0.9	22	11
1.0-1.9	21	10
2.0-2.9	7	4
>3.0	1	1

Two-thirds of the storms in each strata were randomly selected for the development and calibration phase of the study. The remaining one-third of the data was kept separate to independently verify accuracy of the model.

Model Concepts

A general linear model of the hydrologic cycle is:

$$PR = SF + ET + GR \pm \Delta SW$$

where:
PR = Precipitation
SF = Stormflow (surface and subsurface)
ET = Evapotranspiration
GR = Deep seepage to groundwater table
ΔSW = Change in soil water storage
(Rogerson, 1976)

This model operates on a mass balance premise, that is, all precipitation input must be accounted for in one of the output or storage subprocesses.

Soil Water

Rogerson (1976) determined average values of available soil moisture for the surface foot of soil and the remaining profile for soils very similar to those of Watershed I. Rogerson determined the surface foot had about 2.5 inches of available water, and each additional foot of soil had about 1.5 inches of available water. An estimate of initial soil moisture, in inches, was needed as an input for the model.

Available soil moisture values for the entire soil profile were determined for every day of the four years of precipitation and stormflow data using Rogerson's model with precipitation data from Watershed I as inputs (Rogerson, 1985). These values were used as the initial depth of available water in the soil tank for each day on which a precipitation event occurred. The maximum available soil moisture was determined to be 5.4 inches from values for the average solum depth to bedrock for Watershed I. This value was used in the model as the field capacity, or maximum water retention of the soil tank.

The soil moisture values were used in the Clayton model as an initial available soil moisture value, defining a deficit in soil moisture. If the soil profile (soil tank) was saturated, all potential available water was in retention (field capacity), and the soil water deficit was zero. If the soil was unsaturated, a deficit exists, and precipitation was input to the soil until the water deficit was filled (the profile becomes saturated). Any further precipitation was in excess of the retention capacity of the profile and available for use in the stormflow phase.

Evapotranspiration

Since the Clayton model was developed on an event basis, evapotranspiration was assumed to be near zero during and just after a precipitation event due to a high relative humidity. The initial soil moisture values determined by Rogerson (1985) for each day accounted for evapotranspiration during periods of no precipitation and depleted the soil moisture levels accordingly.

Deep Seepage

Deep seepage losses were assumed to be very small or zero during the time of precipitation and recession due to the heavier clay substrata and bedrock. The short period (less than 24 hours after the end of precipitation) of stormflow generation for any storm also supports this assumption. The estimate of field capacity may allow for a small amount of deep seepage by overestimating the maximum retention capacity of the soil.

Stormflow

The stream channels of Watershed I are considered ephemeral as streamflow occurs only in direct response to precipitation. Very low flows (below .05 feet of stage) may last for as much as a week after large spring storms but this is considered to be delayed recession from the upper regions of the watershed.

Conceptually, stormflow comes from direct channel interception and precipitation in excess of the soil moisture storage (i.e. all moisture input after the soil water deficit is filled). Precipitation occurring on the watershed area first filled any soil water deficit that existed. Precipitation in excess of field capacity became stormflow as interflow or percolated to lower soil horizons to be released as delayed subsurface flow.

Direct channel interception was assumed to be one percent of the input precipitation due to a small stream channel area in comparison to the total watershed area. Inclusion of and testing for a variable source area was not considered in this stage of the Clayton model development. Direct channel interception, interflow, and delayed subsurface flow values were in inches of stormflow. Multiplying these depths by an area for Watershed I and converting from minutes to seconds resulted in a stormflow value in cubic feet per second.

Clayton Conceptual Model

Under the assumption (from the preceding discussion) that evapotranspiration and deep seepage will be near zero for the time frame of individual storm events considered, the general linear model can be rewritten;

$$SF = PR - \Delta SW$$

This is the operating concept used for the Clayton model. A graphical representation of the model is shown in Figure 5. The flow diagram includes symbolic representations of vegetative interception and deep seepage loss from the lower soil tank for possible future inclusion in the Clayton model but these areas were not considered in this effort.

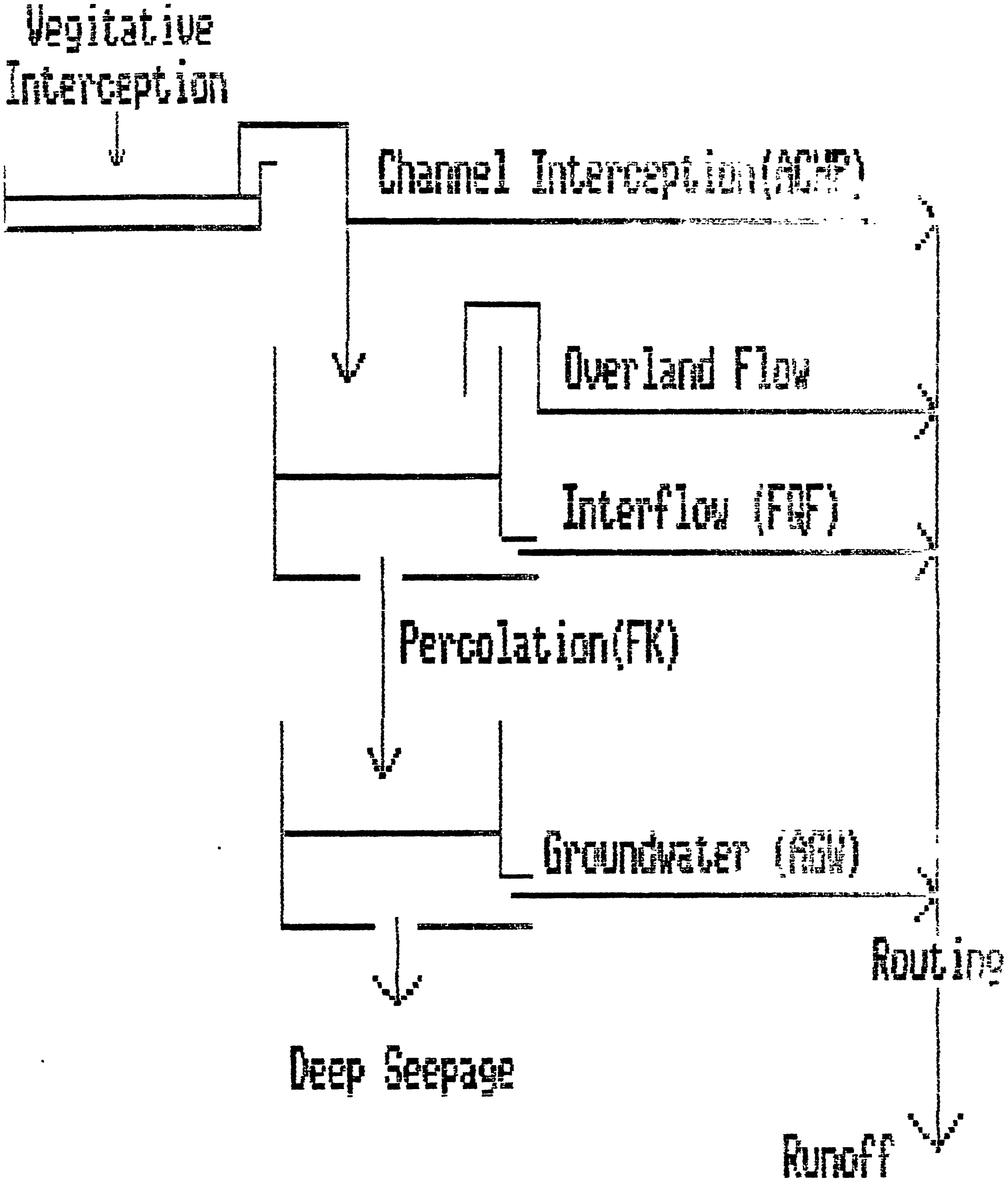


Figure 5. Structure of the Clayton Model

Model Coefficients and Operation

The model used four coefficients and a routing function to predict stormflow from input parameters. The coefficients were: direct channel interception, ACHP; interflow, FQF; delayed recession, AGW; and percolation, FK. The routing function is described in a following section.

The model operates on a storm by storm basis. For any storm, initial soil moisture depth and the first non-zero precipitation depth for the storm were input. The soil moisture level was first checked to see if it was at or above 5.00 inches. At 5 inches of available soil moisture it was assumed that the soil near the channel was nearing saturation and direct channel interception would start occurring. Channel interception was calculated by multiplying the input precipitation by the channel interception coefficient (ACHP). The channel interception, in inches, was subtracted from the input precipitation. The rest of the input precipitation was then infiltrated into the soil tank. Soil moisture depth was checked against the 5.4 inch field capacity level to see if any moisture was available for stormflow.

If soil moisture was below field capacity the input precipitation was added to the soil moisture total and the next precipitation increment was input until field capacity was reached. When the soil moisture was above field capacity the depth of excess soil moisture was calculated as soil moisture minus field capacity. This excess depth value was then multiplied by the interflow coefficient (FQF) and percolation coefficient (FK). The calculated interflow value was stored as inches of stormflow for that time increment. The percolation value (in inches) was added to the groundwater storage. The soil moisture in the groundwater storage tank was then multiplied by the groundwater coefficient (AGW) to determine the delayed stormflow from the groundwater tank for the same time increment. Soil moisture was depleted by the sum of the interflow and percolation values. The groundwater storage was depleted by the amount of delayed stormflow and the model returned to the start for input of the next precipitation increment.

Routing Function

Since the model is lumped, any stormflow output occurs at the same time as the precipitation input that produced it. This results in a hydrograph that has many small sharp peaks which do not appear on the observed hydrograph. The observed hydrograph for any storm shows smoother rise and fall of stormflow volume over time. This is due to greater travel time for stormflow from precipitation occurring on the upper portions of Watershed I to reach the watershed outlet as compared to the travel time for stormflow from precipitation occurring at the same time on portions closer to the watershed outlet. To estimate the travel time of water from points of generation on the watershed to the monitoring point a routing function was needed. This function would simulate the delay and distribute the predicted stormflow with respect to time in order to better represent the shape of a stormflow hydrograph. Initially a simple ten step routing function was incorporated into the model. This consisted of ten coefficients, the sum of which is 1. The output at any time, then, is a function of the coefficients times the ten previous output values. The following example serves to illustrate the nature of the distribution function.

Given:

T_n = 15 minute time increment number (n)
Q_n = Predicted rainfall excess depth from model at time n
V_n = Volume of stormflow that is output by the model at n
RF_x = Routing function values (x = 1 to 10)

The volume of stormflow (V) at T_1 is:

$V_1 = Q_1 \text{ x } RF_1$

and for T_2:

$V_2 = (Q_2 \text{ x } RF_1) + (Q_1 \text{ x } RF_2)$

and for T_3:

$V_3 = (Q_3 \text{ X } RF_1) + (Q_2 \text{ X } RF_2) + (Q_1 \text{ X } RF_3)$

This routing procedure effectively distributed the stormflow from any one input of precipitation to the model over a period of two and a half hours (ten 15 minute stormflow increments). The values of the ten coefficients were determined by the methods described below in the calibration section.

Sensitivity Analysis

Once all the model subsystems were operating, a sensitivity analysis was conducted on the model to determine the most sensitive of the four coefficients. The criterion for sensitivity was magnitude of change in the model output caused by a small change in coefficient value. Changes in output were qualitatively evaluated by comparing predicted output hydrographs for each coefficient value to graphs of the observed stormflow.

While the subsystems were being programmed the author used one calibration storm as a source of data to test the subsystem outputs.

During this developmental stage values of the four coefficients for this one storm were determined by trial and error. Using these base values, the model was run holding three of the four coefficients constant. The model was iterated at 25, 50, 100, 125, and 150 percent of the initial value of the respective coefficient. Predicted stormflow was plotted against actual stormflow for each coefficient percentage value and compared. This was done for the FQF, AGW, and FK coefficients. It was assumed the ACHP coefficient would be highly insensitive, requiring a large change from the base value to show a marked change in model output. Percentages of the ACHP values used for sensitivity testing therefore were 10, 50, 100, 150, and 250.

FQF and AGW were found to be the most sensitive coefficients. FK was slightly sensitive, and ACHP was found to be highly insensitive. An increase in the FQF coefficient would result in a generally faster rate of rise and fall of the predicted hydrograph and an increase in the peak flow volume. AGW was mainly responsible for the shape of the recession limb of the hydrograph, that is, it controlled the rate of groundwater recession. An increase in the AGW coefficient would slightly increase the peak flow rate, and would increase the total flow volume by allowing delayed recession to occur at a faster rate. An increase in the FK coefficient would allow more water to seep into the lower soil horizons, reducing the amount of water available for interflow and increasing that available for delayed recession. Increasing the ACHP coefficient would increase the peak flow rate a very small amount.

This analysis provided a working knowledge of the magnitude and direction of the effect a change in each coefficient had on the model's prediction of peak flow rate and total flow volume. This was used in the calibration phase of model development.

Calibration

Calibration of the four coefficients and the routing function using the 96 calibration storms was done on a trial and error basis. Using the base values (described in the sensitivity analysis section) for the four coefficients as initial input values, each test storm was iterated through the model. Adjusting the coefficients with each iteration, a "best fit" of the predicted peak flow rate and total flow volume as compared to the actual values for each storm was attained.

The initial run on each new storm was made using the coefficient values from the previously completed storm. Adjustments were then made, one at a time, to the most sensitive parameters (FQF and AGW) first, then to the routing functions, then FK, then ACHP. After each iteration the predicted versus actual flow volume and peak were compared. Respective coefficients were adjusted to reduce these differences, and the model run once again. This process continued for each storm until the change in a coefficient would have little effect in minimizing the output differences (plus or minus 1.0 for flow volumes and 0.05 for peak flow rates). At that point the coefficient values, the routing values, the predicted and actual flow volume and peak flow rate, and a graph of the actual and predicted stormflow hydrograph were saved for further analysis.

CHAPTER IV

RESULTS AND DISCUSSION

Calibration

For the calibration phase of the Clayton model only storms with a peak flow rate greater than 0.1 cubic feet per second (cfs) were considered. Of the 96 calibration storms considered, 55 produced stormflow, and 31 of those storms produced flow greater than 0.1 cfs at the peak. A mean value for each of the four coefficients was determined from calibration coefficient values for the 31 larger storms. The routing function values were determined by the most frequently used distribution and positions (1 through 10).

Mean values for the four coefficients are presented in Table II. The most frequently used distribution and positions for the routing function are presented in Table III. This distribution and positioning of the routing function values occurred in 12 of the 31 test storms, and in 9 other storms the same distribution shifted left or right of the positions given in Table III. These mean coefficient values and the routing function values were therefore used in the verification phase of the project.

TABLE II

MEAN MODEL COEFFICIENT VALUES FROM 31 CALIBRATION STORMS

Coefficient	Symbol	Mean Value	Standard Error
Interflow	FQF	0.042	0.007
Groundwater	AGW	0.011	0.002
Percolation	FK	0.40	0.037
Channel Interception	ACHP	0.01	0.001

TABLE III

MOST FREQUENTLY USED ROUTING DISTRIBUTION AND POSITION

Routing Function										
Position	1	2	3	4	5	6	7	8	9	10
Value	0.0	0.0	0.0	0.1	0.1	0.3	0.3	0.1	0.1	0.0

An attempt to fit a continuous probability distribution to the output that would have some basis in the physical environment was made. From the theory of cascading reservoirs (Haan, et. al., 1982) and the continuity equation a distribution similar to a gamma distribution can be derived (Equation 1).

$$RF_x = \frac{1}{K(n-1)!} (\Delta t/K)^{n-1} \exp(-\Delta t/K) \qquad (1)$$

The n parameter represents the number of linear reservoirs connected in series, so output from one reservoir becomes the inflow to the next reservoir and K represents the storage constant of each reservoir. The larger the number of reservoirs the lower the peak and more attenuated the predicted stormflow curve.

The n and K parameters were estimated using the method of moments The first moment is defined as the mean stormflow or rainfall excess value about the origin. Equation 2 shows the relationship between the first moments.

$$M_{D1}-M_{E1} = nK \qquad (2)$$

where: ·

M_{D1} = first moment of the observed stormflow hydrograph

M_{E1} = first moment of the predicted rainfall excess hyetograph

The nK product equals the first moment around the mean rainfall excess rate. For a gamma distribution the variance of the observed stormflow hydrograph equals nK^2. Solving for n and K from these two equations a routing function value at any time step can be calculated from Equation 1. For RF_{x-1}, $\Delta t = 2\Delta t$, and so on for each successive function value. Stormflow values were then calculated in the same manner as the ten-step routing function. For this application the sum of RF values at 200 equaled approximately 0.99.

This method did not fit the predicted stormflow hydrograph to the observed stormflow hydrograph with acceptable accuracy. In fact, it was visually much less accurate than the ten step routing function described above. Routing functions fitted by the method of moments as as described above were not capable of predicting the early, sharp peaks of the observed stormflow, as shown in Figure 6.

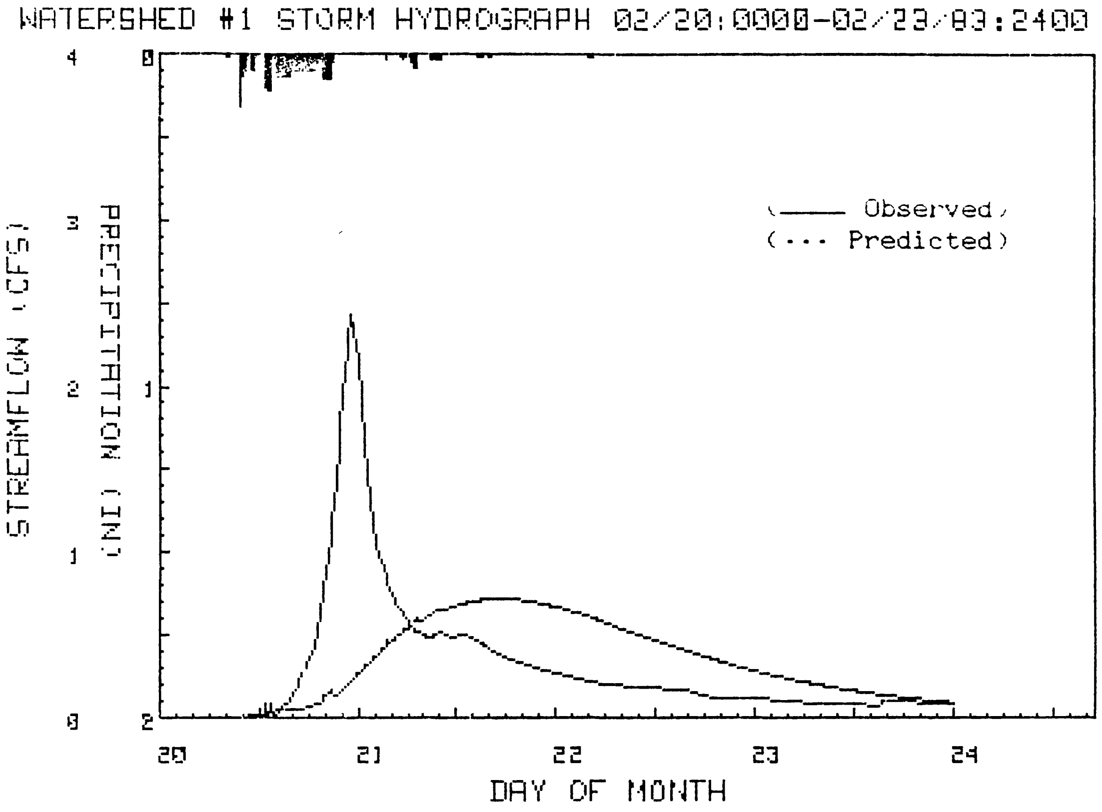


Figure 6. Graph of Observed Versus Continuous Distribution Runoff Hydrograph

An attempt was then made to use the interflow coefficient, FQF, as the value for K in Equation 1 and solve for n with one equation. Since the value of K represents the storage constant for the n linear reservoirs, it was assumed that the interflow coefficient for the soil tank would be similar, and the interflow (FQF) value had been calibrated to the data from the watershed. This method produced nK products similar to the moments method, and thus similar results were obtained. No further attempts were made to fit a continuous distribution function to the output. The ten step routing function was used in the verification phase due to time constraints.

Verification

Using the mean coefficient values and the ten step routing function values, the 49 verification storms were used to test the model's prediction capability. Of the 49 verification storms, 18 were above 0.1 cfs at the peak. These 18 storms were used for the following analyses.

The percent error ((observed - predicted)/observed x 100) between the observed and predicted peak flow rate and total flow volume for each storm was calculated. The model tended to overpredict both the peak flow rate and the total flow volume when compared to the observed data. The mean percent error for the model's prediction of the observed peak flow rate was -23.1 percent with a standard error of 22.6 percent. The mean percent error for the model's prediction of observed flow volume was -25.5 percent with a standard error of 119.1 percent.

The number of verification storms occurring in various percent error ranges were calculated for peak flow and total flow volume (Table IV). Actual percent errors for peak flow rate prediction ranged from

-201% to +87%. Actual percent errors for prediction of flow volume ranged from -319% to +95%. Examples of some of the best and poorest fits for peak flow rate and total flow volume are presented in Figures 7 and 8.

TABLE IV

DISTRIBUTION OF STORMS BY PERCENT ERROR (ACTUAL VERSUS PREDICTED)

Percent Error	Peak flow Rate	Total Flow Volume
<-91	4	4
-90 to -71	1	1
-70 to -51	1	0
-50 to -31	0	1
-30 to -11	3	2
-10 to +9	0	0
+10 to +29	1	3
+30 to +49	3	1
+50 to +69	2	3
+70 to +89	3	1
>+90	0	2

Plots of the residual (actual minus predicted) values for peak flow rate versus total precipitation depth and initial soil moisture depth are presented in Figure 9. Plots of the residual total flow volume versus precipitation and initial soil moisture are presented in Figure 10. Visual analysis of these plots shows no detectable pattern of the plotted residuals about the zero line. This would indicate that no bias

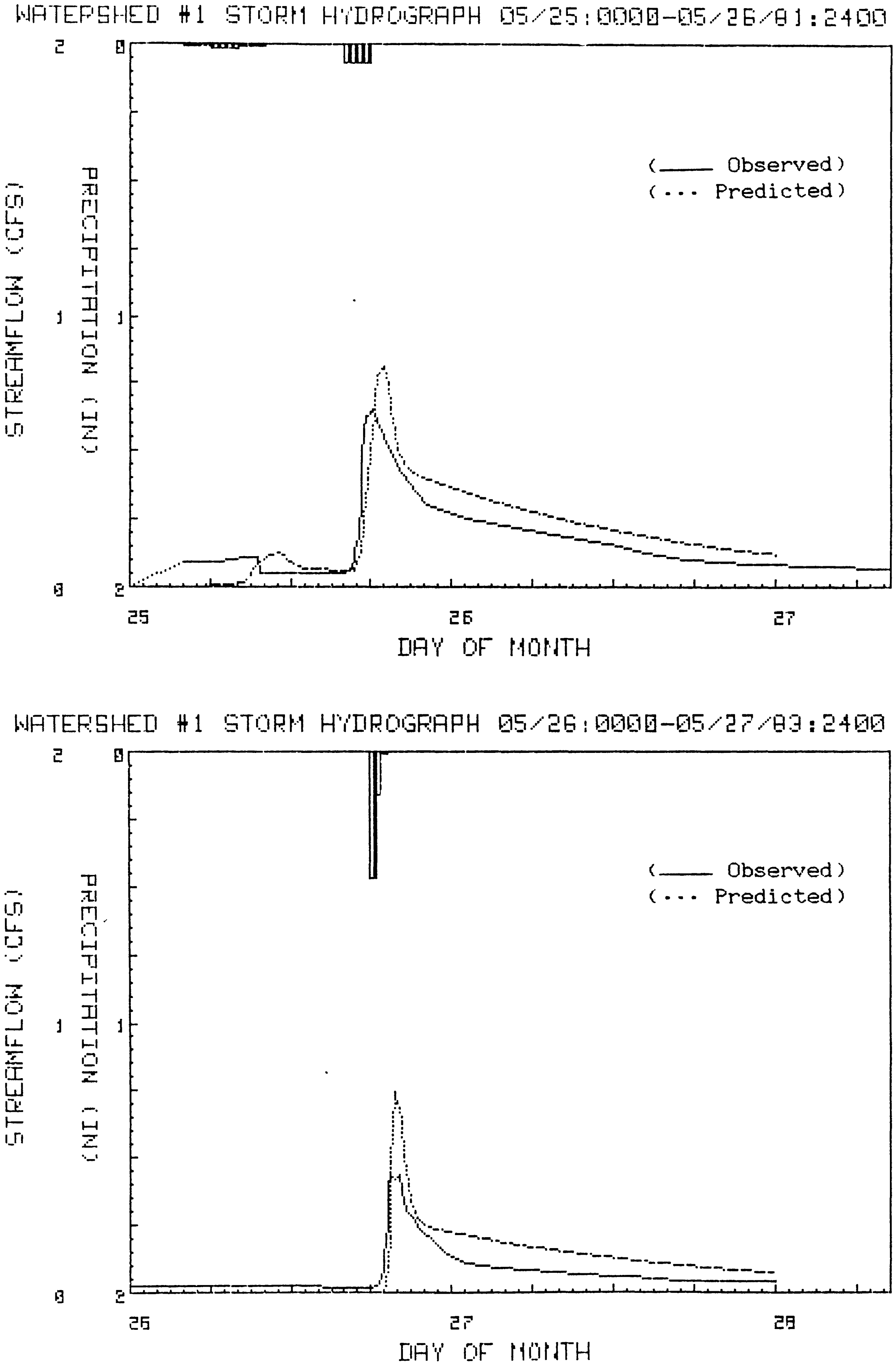
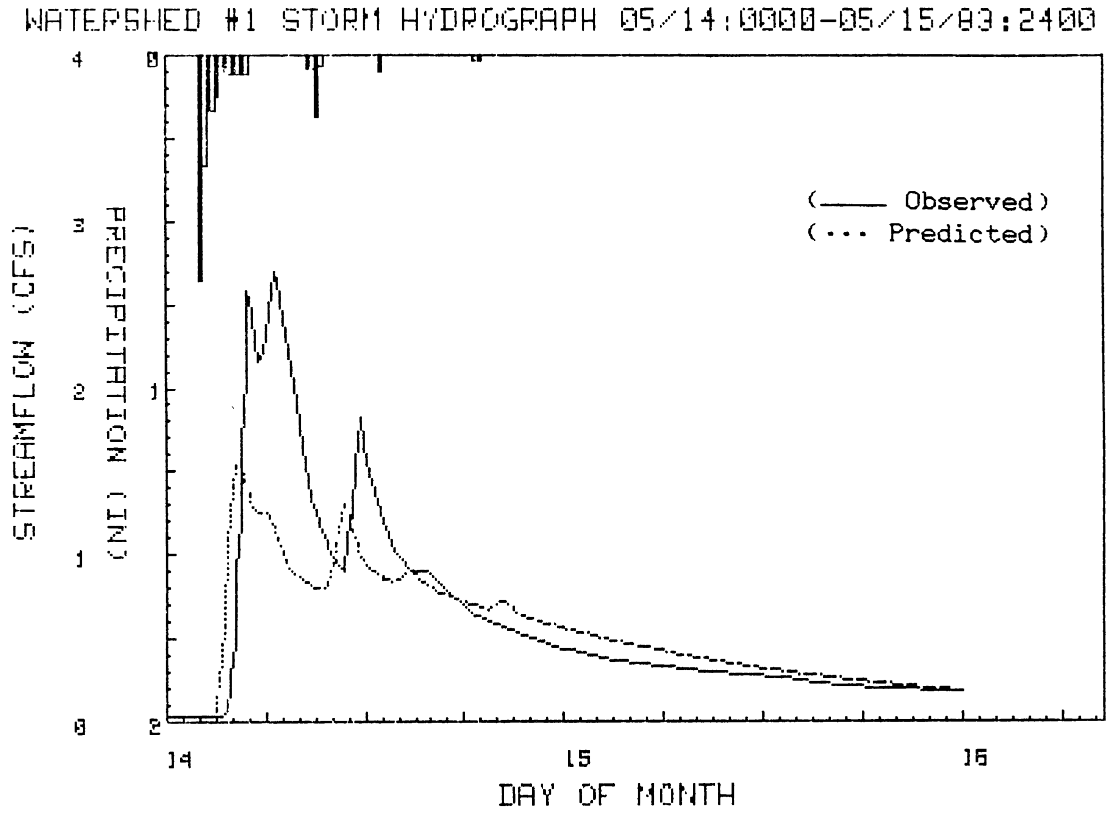
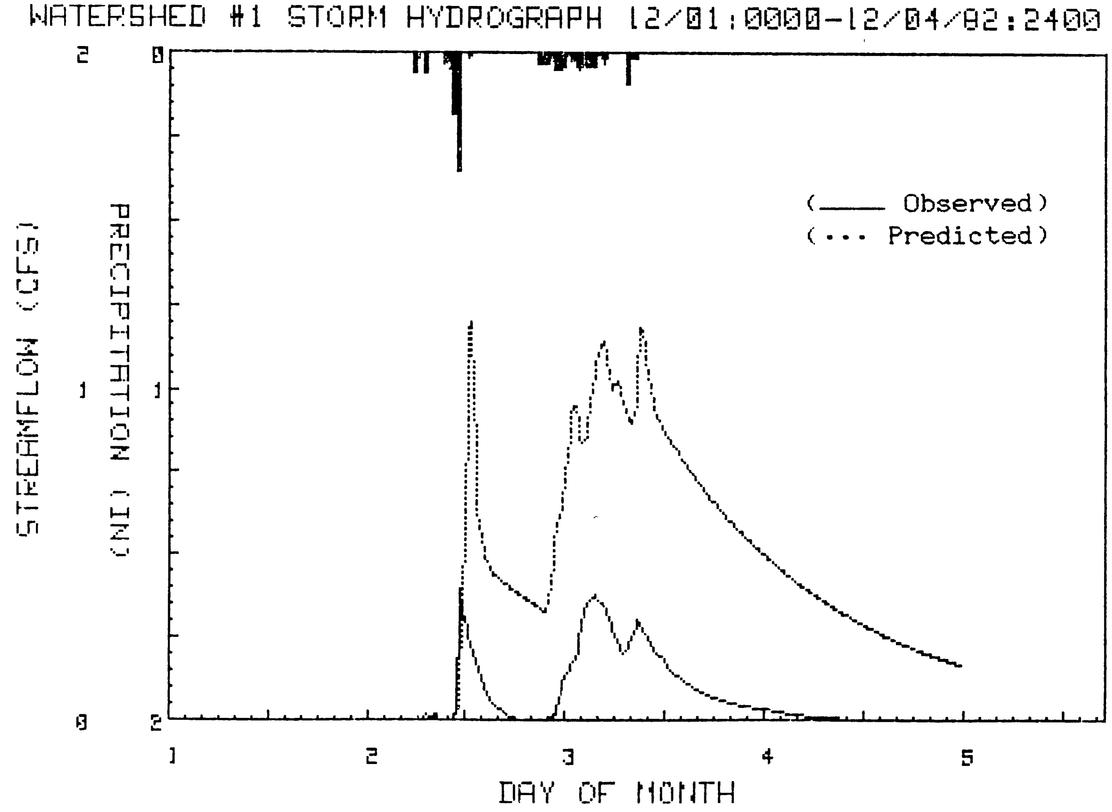


Figure 7. Two "Best" Fit Storms From the Verification Phase



WATERSHED #1 STORM HYDROGRAPH 05/14:0000-05/15/83:2400



WATERSHED #1 STORM HYDROGRAPH 12/01:0000-12/04/82:2400

Figure 8. Two "Poorest" Fit Storms From the Verification Phase

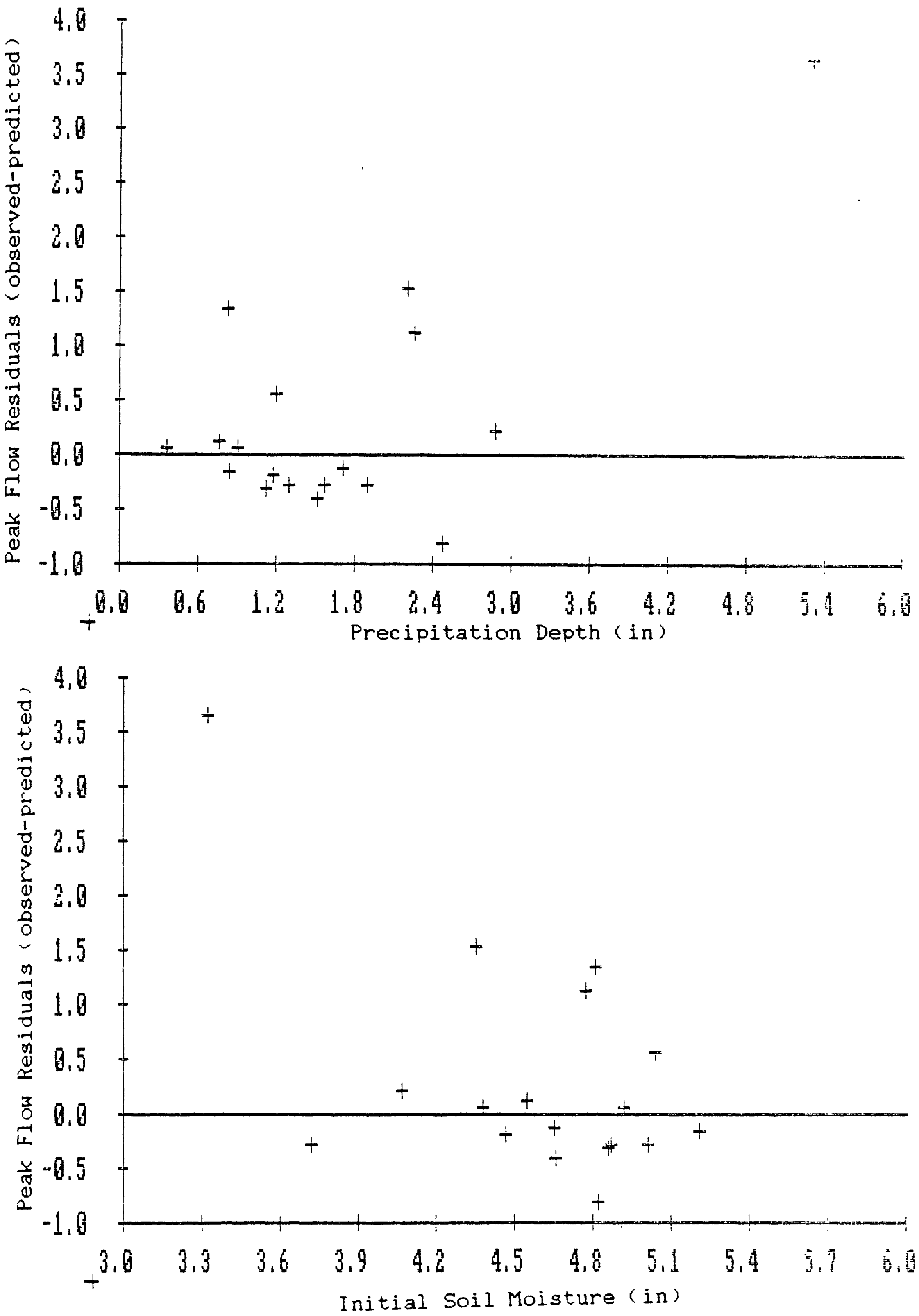


Figure 9. Plots of Peak Flow Residuals Versus Input Precipitation and Soil Moisture

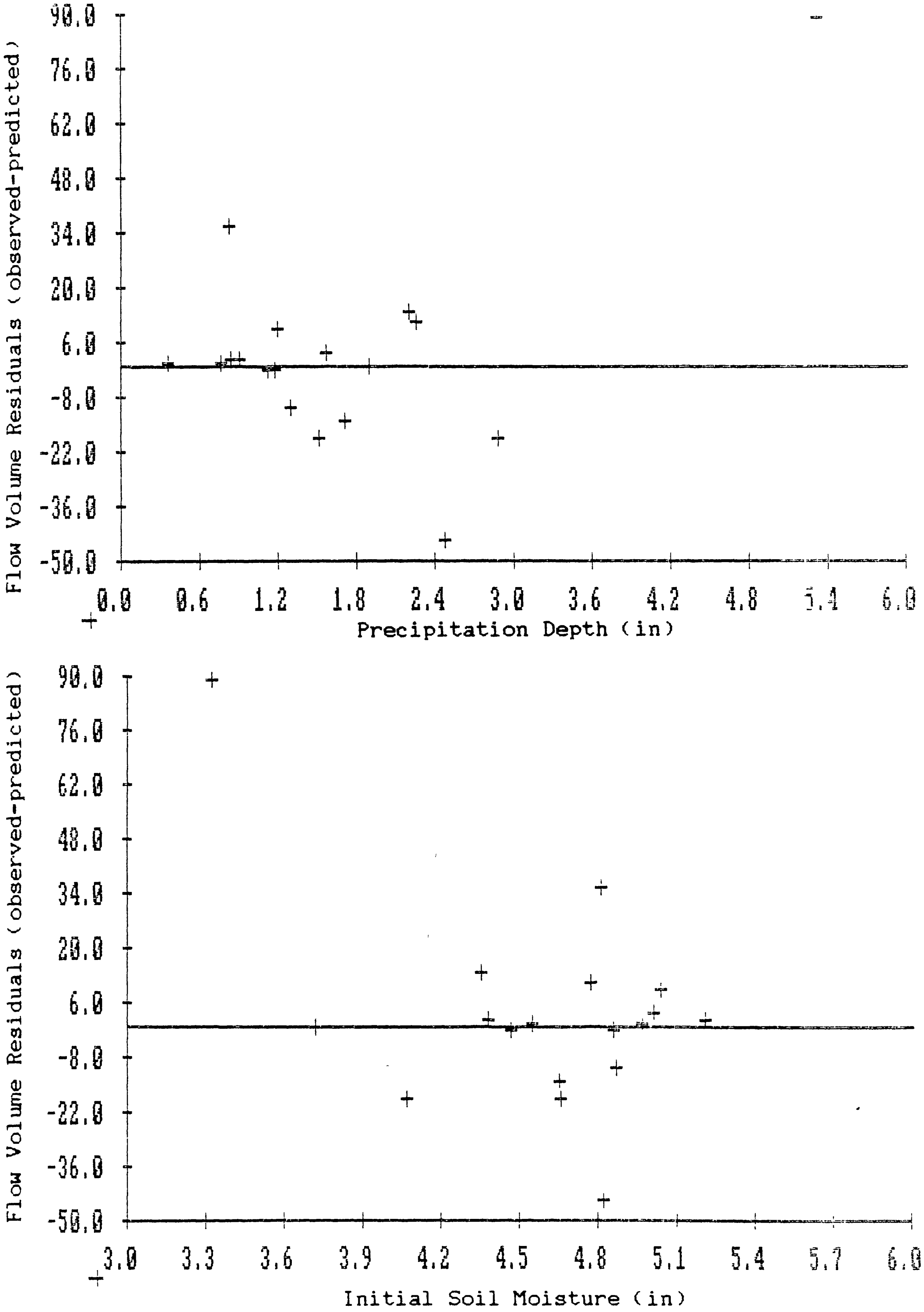


Figure 10. Plots of Flow Volume Residuals Versus Precipitation and Soil Moisture

exists in the model, that is, modeling errors are randomly distributed over the entire range of input values.

A paired-t test conducted on the peak flow residuals indicates that the mean peak residual is not significantly different from zero ($p = 0.05$). The mean peak residual was 0.328 cfs with a standard error of 0.246. The sum of the residual peak flow values was 5.9 cfs, and the mean absolute peak residual was 0.639 cfs.

A paired-t test conducted on the total flow volume residuals indicates that the mean flow residual is not significantly different from zero ($p = 0.05$). The mean flow residual was 704,762 cubic feet, with a standard error of 1,020,786. The sum of the total flow volume residuals was 13,390,488 cubic feet, and the mean absolute flow volume residual was 2,053,254 cubic feet.

Areas for Further Refinement

The predictive capability of the model may be improved by further analysis of certain processes. One area is the initial soil moisture values and related field capacity as determined by Rogerson (1985). After determination of the verification results reported above, an optimization of the initial soil moisture values used as inputs for each of the 18 verification storms was conducted. This was done by iterating each storm through the model, raising or lowering the initial soil moisture value with each iteration to raise or lower the resulting predicted hydrograph until the difference between the observed and predicted values was minimized.

From this analysis it was observed that initial soil moisture values appeared to be overpredicted in the months of April and May.

This corresponds to the months of heavy precipitation in southeast Oklahoma. Of the 18 verification storms, 11 occurred in April or May. The initial soil moisture values for the remaining storms appeared to be underpredicted. It is important to note that all but one of the verification storms occurring in April and May required a reduction in initial soil moisture, while all other storms required an increase in soil moisture to reduce differences in observed versus predicted values.

It is possible that the input initial soil moisture values, since they are predicted values from a model, may contain some seasonal error. Any consistent error in these inputs should have been compensated for in the calibration phase, resulting in smaller coefficient values for April and May, and larger coefficient values in other months. Since mean coefficient values were used trends still could occur.

Adjustment of either the initial soil moisture or field capacity values by a constant positive or negative value would not improve the prediction accuracy of the model. Raising the field capacity would improve the prediction of those storms in April and May by requiring more input precipitation to fill the soil tank to retention capacity, thus negating any overprediction of the initial soil moisture, but storms in other months with possibly underpredicted initial soil moisture values would also have to fill the added retention capacity. This could greatly reduce the amount of stormflow predicted as compared to actual for summer and fall storms. Also, any change in field capacity would invalidate the initial soil moisture inputs as they were calculated using 5.4 inches as the maximum soil moisture retention capacity. A study to test Rogerson's model on Watershed I using on-site soil moisture data may point out areas in Rogerson's model needing further calibration to better predict soil moisture values for Watershed I.

For the four years of recorded stormflow data used in developing the Clayton model, April and May storms accounted for 49.1 percent of the total stormflow, followed by June (16.8%), and February (13.6%). Changing the field capacity values to obtain better predictions for April and May storms may be acceptable as those storms produce the majority of flow, and greater accuracy in predicting them is desirable.

From the sensitivity analysis it was concluded that the channel precipitation coefficient (ACHP) was insensitive. This conclusion was based on a variation of the ACHP value from 10 to 250 percent the initial value. Since the initial value was only one percent, the highest value for direct channel precipitation analyzed has only 2.5 percent of the watershed area contributing to direct stormflow from direct channel interception. A saturated source area could potentially occur over 30+ percent of the watershed area. Thus, the sensitivity analysis conducted did not fully explore the possibility of having a large saturated area on the watershed contributing to stormflow.

The incorporation of a variable source area into the model is a structural change that would allow for variation in seasonal conditions on Watershed I. One equation representing a variable source area was developed by Federer and Lash, and presented in Sloan et al. (1983), for the BROOK model of forested watersheds in New Hampshire (Equation 3).

$$Y = M + N(\exp(ri)) \tag{3}$$

where:

Y = fractional amount of precipitation converted to direct stormflow
M = fraction of stream area in the watershed

i = soil moisture value
N and r are constants

With increasing channel expansion related to increasing soil moisture content, more input precipitation would fall on saturated surfaces and be converted to stormflow (that would infiltrate into the soil in dryer months) with the expansion of the stream channel in the spring due to frequent rainfall. Summer and fall storms that generally produce smaller stormflow events may also be better predicted by a model that uses a variable source area. Since stormflow could occur without completely filling the soil retention capacity, and stormflow would increase as soil moisture increased, very low flows would be predicted.

Further attempts to fit a continuous probability distribution to the predicted rainfall excess may improve the prediction capacity of the model. It is noteworthy that the ten step routing function, while highly empirical and only applicable to Watershed I, did a very reasonable job of distributing the rainfall excess to produce a stormflow hydrograph in both the calibration and verification phase of the project. Expanding the channel precipitation may allow for a faster rise to peak, a model weakness for many storms, and consequently a continuous distribution routing function may not be needed.

Making any structural change in the model would necessitate the re-calibration of all coefficients and the routing function, along with any new coefficients used in the added structure. Other possible analyses include the testing of ranges of coefficients related to input precipitation depth or seasonal values for coefficients.

CHAPTER V

Summary

A rainfall-runoff computer model was developed for ephemeral watersheds in southeastern Oklahoma. The model used only precipitation and initial soil moisture content as inputs. It was based on modeling work done by Shih, Hawkins, and Chambers (1976) on forested watersheds in Utah and Oregon. The model structure consisted of a main soil tank with a given soil moisture retention capacity. Any infiltrating water that was in excess of the retention capacity would produce stormflow. Part of this excess water drained into a lower soil tank which then contributed to delayed groundwater flow.

Four coefficients and a simple ten-step routing function were calibrated to the watershed by trial and error. The four coefficients controlled movement of water in four processes: direct channel precipitation; interflow; percolation; and groundwater recession. Direct channel precipitation was converted to stormflow as a percentage of input precipitation. Interflow and percolation were calculated as a percentage of the soil moisture in excess of the maximum soil moisture retention value. Groundwater recession was calculated as a percentage of soil moisture in the lower soil tank. The routing function consisted of a distribution of 10 coefficients that summed to one. Every stormflow output from the model was multiplied by each of the coefficients. Each routing coefficient represented a 15 minute delay from the time of input to the time of output, so any one calculated stormflow output from the model was distributed over a 2.5 hour period.

Of the 145 separate storms on record, 96 were used in the calibration phase, and 49 were used for independent verification of the model coefficients. Mean values for the four coefficients were determined from the calibration phase. Only storms that produced a peak flow rate of 0.1 cfs or greater (31 storms) were considered in determining the mean coefficient values and routing function from the calibration data. The verification data was then run through the model using the mean coefficient values and routing function. Only storms with peak flow rates of 0.1 cfs or greater (18 storms) were considered in the verification analysis.

Results of the verification analysis data indicated that on the average the model overpredicted peak flow rates by 23 percent and total flow volumes by 25 percent, though actual values varied from -95 to +300 percent. A paired-t test of the mean residuals for peak flow rate and total flow volume indicated that the mean residuals were not significantly different from zero.

Initial soil moisture values used as inputs were predicted from a model developed by Rogerson (1976). From an optimization analysis of the soil moisture inputs a seasonal trend was observed. Spring storms may have predicted initial soil moisture values too high as compared to the rest of the year. Adjustments to the maximum soil moisture retention value (field capacity) would invalidate the initial soil moisture values used as input to the model as they were predicted using a field capacity value of 5.4 inches. Further research and testing of

Rogerson's model on watersheds geographically closer to Watershed I may improve prediction of initial soil moisture values.

For the verification phase areal channel precipitation was assumed to be only one percent of the watershed area. It is possible that the saturated channel area may be much greater, and may vary with season. Changes in the model structure may be necessary to compensate for seasonal variations on Watershed I. Incorporating a variable source area into the Clayton model is one possible structural change. A large source area may be present on the watershed in the spring months during times of heavy precipitation. Allowing for an expanded channel during wet periods may enable the model to better predict stormflow.

Incorporation of any or all of the above possible changes in the model will require re-calibration of existing coefficients and calibration of any new coefficients. Further analysis of the coefficients is needed, with an emphasis on relating coefficient values to inputs or watershed parameters. From this analysis it may be possible to predict coefficient value ranges that match either storm size, time of year, or some physical aspect of any watershed.

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APPENDIX A

CLAYTON MODEL PROGRAM LISTING

```
10        SET TIME 0
20        Page=0
30        Achplimit=5.0
40        Ddd=0     !Set routing function values
50        E=0
60        G=0
70        Hhh=.1
80        J=.1
90        Dd=.3
100       Ee=.3
110       Gg=.1
120       Hh=.1
130       Jj=0
140       Saveiq=0 !140-170 sets conditions for reading storm dates
150       Saveip=0 !from "STORMDATES" file
160       Stnum=0
170       Err=0
180       Achp=.01 !Set initial coefficient values
190       Fk=.4
200       Fqf=.041968
210       Agw=.011448
220       Gwl0=0.
230       Fc=5.4
240       Storm$="STORMDATES"
250       MASS STORAGE IS ":HP8290X,700,1"
260       ASSIGN @Main TO Storm$
270       GOSUB Year
280       REPEAT

          !read first storm number,scalar date,init. SM, and counter
       value for use in "MCPSTORMS" file (contains storm start and end)

290          READ Stnum
300          ENTER @Main,Stnum;Wsc,Datec,Sm0c,Stnc
310          SM0=Sm0c
320          GOSUB Mcwow
330          READ Stnum
340          ENTER @Main,Stnum;Wsc1,Datec1,Sm0c1,Stnc1
350          IF Datec1<DatecTHEN
360             GOSUB Year
370             GOTO 290
380          END IF
390          Datec=Datec1
400          Sm0c=Sm0c1
410          Sm0=Sm0c
420          Stnc=Stnc1
430          Wsc=Wsc1
440          GOSUB Mcwow
460          GOTO 330
470       UNTIL Stnum=145
480       DATA 7,11,13,15,17,18,20,24
490       DATA 28,29,33,35,39,40,43,44,45,46,49,50,55,56
500       DATA 64,65,68,71,73,75,84,85,87,88,89,92,93
```

```
510      DATA 95,99,102,103,104,108,112,117,120,127,130,135,136,140,142

         !Year allows for changing disks, closing files, opening files,
         and calculating total runtime up to disk change

520  Year:    CHANGE DISK FOR NEW YEAR
530      ASSIGN @Main TO *
540      ASSIGN @Route TO *
550      ASSIGN @Path TO *
560      Sec=TIMEDATE MOD 86400
570      PRINT "MINUTES=",Sec/60
580      SET TIME 0
590      PRINT "INSERT APPROPRIATE DATA DISK AND PRESS CONTINUE"
600      PAUSE
610      INPUT "ENTER YEAR NUMBER OF DATA (ONLY THE STARTING YEAR,
  e.g.1980)",Tyr
620      IF Tyr<=1978 OR Tyr>1982 THEN
630      PRINT "TRY AGAIN"
640         WAIT 1
650         GOTO 610
660      END IF
670      IF Tyr=1979 THEN
680         Flow$="WS17980I"
690         Rain$="PCP17980I"
700         Saveip=0 !Holds reading head over current prec file
710         Saveiq=0 !Holds reading head over current flow file
720         RESTORE 480
730      END IF
740      IF Tyr=1980 THEN
750         Flow$="WS18081I"
760         Rain$="PCP18081I"
770         Stnum=24
780         Err=48
790         Saveip=0
800         Saveiq=0
810         RESTORE 490
820      END IF
830      IF Tyr=1981 THEN
840         Flow$="WS18182I"
850         Rain$="PCP18182I"
860         Stnum=62
870         Err=124
880         Saveip=0
890         Saveiq=0
900         RESTORE 500
910      END IF
920      IF Tyr=1982 THEN
930         Flow$="WS18283I"
940         Rain$="PCP18283I"
950         Stnum=94
970         Saveip=0
980         Saveiq=0
```

```
990          RESTORE 510
1000      END IF
1010      Storm$="STORMDATES"
1020      ASSIGN @Main TO Storm$
1030      ASSIGN @Route TO Flow$
1040      ASSIGN @Path TO Rain$
1050      RETURN
1060   Mcwow:      MODEL
1070      DIM P(470),Qxs(470),Qof(470),Qf(470),Q(470),Qcf(470),Qchp(470),
   Fd(470),Qgw(470),Sm(470),Gwl(470),Rq(470)

               !Clear all matrix registers

1080      FOR Www=1 TO 470
1090         P(Www)=0
1100         Qxs(Www)=0
1110         Qof(Www)=0
1120         Qf(Www)=0
1130         Q(Www)=0
1140         Qcf(Www)=0
1150         Qchp(Www)=0
1160         Fd(Www)=0
1170         Qgw(Www)=0
1180         Sm(Www)=0
1190         Gwl(Www)=0
1200      Rq(Www) = 0
1210      NEXT Www
1220      PRINT CHR$(12)
1230      Corr$="MCPSTORM"
1240      MASS STORAGE IS ":HP8290X,700,0"
1250      ASSIGN @Way TO Corr$
1260      GOTO 1510

          !Scalar date routine

1270      Date=0
1280      IF M=10 THEN Date=Date+0
1290      IF M=11 THEN Date=Date+31
1300      IF M=12 THEN Date=Date+61
1310      IF M=1 THEN Date=Date+92
1320      IF M=2 THEN Date=Date+123
1330      IF Y=80 OR Y=84 OR Y=88 OR Y=92 OR Y=96 THEN GOTO 1420
1340      IF M=3 THEN Date=Date+151
1350      IF M=4 THEN Date=Date+182
1360      IF M=5 THEN Date=Date+212
1370      IF M=6 THEN Date=Date+243
1380      IF M=7 THEN Date=Date+273
1390      IF M=8 THEN Date=Date+304
1400      IF M=9 THEN Date=Date+335
1410      GOTO 1490
1420      IF M=3 THEN Date=Date+152
1430      IF M=4 THEN Date=Date+183
```

```
1440      IF M=5 THEN Date=Date+213
1450      IF M=6 THEN Date=Date+244
1460      IF M=7 THEN Date=Date+274
1470      IF M=8 THEN Date=Date+305
1480      IF M=9 THEN Date=Date+336
1490      Date=Date+(D-1)+(Hr/24)+(Min/1440) !Scalar Date
1500      RETURN
1510      GCLEAR
1520      MASS STORAGE IS ":HP8290X,700,1"
1530      ASSIGN @Route TO Flow$
1540      MASS STORAGE IS ":HP8290X,700,1"
1550      ASSIGN @Path TO Rain$
1560      IF Skip=1 THEN GOTO 2810 !Calibration, skips redraw of screen
1570      Err=0
1580      Err=Stnum*2-1
1590      IF Stnum=1 THEN Err=1

          !Read storm starting time and date

1600      ENTER @Way,Err;M,D,Y,Hr,Min
1610      M1=M
1620      D1=D
1630      Y1=Y
1640      Hr1=Hr
1650      Min1=Min
1660      GOSUB 1270  !Determine scalar date
1670      Begdate=Date !Major start value used in several loops of model
1680      Err=Err+1

          !Read storm ending time and date

1690      ENTER @Way,Err;M,D,Y,Hr,Min
1700      M2=M
1710      D2=D
1720      Y2=Y
1730      Hr2=Hr
1740      Min2=Min
1750      GOSUB 1270
1760      Enddate=Date  !Scalar end date for storm
1770      Tdur=Enddate-Begdate

          !1780 - 1970 determines the X-axis scale in days of time

1780      IF Tdur<=2.5 THEN
1790        Tmax=D1+2.5
1800        Tscale=48
1810      END IF
1820      IF Tdur>2.5 AND Tdur<=5 THEN
1830        Tmax=D1+5
1840        Tscale=24
1850      END IF
1860      IF Tdur>5 AND Tdur<=10 THEN
```

```
1870         Tmax=D1+10
1880         Tscale=12
1890      END IF
1900      IF Tdur>10 AND Tdur<=15 THEN
1910         Tmax=D1+15
1920         Tscale=8
1930      END IF
1940      IF Tdur>15 AND Tdur<=30 THEN
1950         Tmax=D1+30
1960         Tscale=4
1970      END IF
1980      I=(Saveiq-3) !Starts read of disk 3 before start time
1990      IF Saveiq=0 THEN I=0
2000      REPEAT
2010         I=I+1
2020         ENTER @Route,I;Ws,Date,Cfs
2030         IF Ws=9 THEN GOTO 2060
2040         IF Date>=Begdate THEN GOTO 2060
2050      UNTIL Date=Begdate !First flow record of storm
2060      I1=I !Loop start value for any seach of flow data records
2070      Qmax=0
2080      REPEAT
2090         I=I+1
2100         IF Ws=9 THEN GOTO 2190
2110         ENTER @Route,I;Ws,Date,Cfs
2120         IF Ws=9 THEN GOTO 2190
2130         IF Cfs>Qmax THEN
2140            Qmax=Cfs
2150         END IF
2160         Saveiq=I
2170         Cfsmax=Qmax
2180      UNTIL Date>=Enddate

          !2190 - 2380 determines Y-axis streamflow scale

2190      IF Qmax<=2 THEN
2200         Qmax=2
2210         Qscale=40
2220      END IF
2230      IF Qmax>2 AND Qmax<=4 THEN
2240         Qmax=4
2250         Qscale=20
2260      END IF
2270      IF Qmax>4 AND Qmax<=8 THEN
2280         Qmax=8
2290         Qscale=10
2300      END IF
2310      IF Qmax>8 AND Qmax<=16 THEN
2320         Qmax=16
2330         Qscale=5
2340      END IF
2350      IF Qmax>16 AND Qmax<=32 THEN
```

```
2360        Qmax=32
2370        Qscale=2.5
2380     END IF
2390     I=(Saveip-3)
2400     IF Saveip=0 THEN I=0
2410     REPEAT
2420        I=I+1
2430        ENTER @Path,I;Ws,Date,Ipcp,Pcp
2440        IF Ws=9 THEN GOTO 2460
2450     UNTIL Date>=Begdate
2460     I2=I  !Loop start value for any search of precipitation records
2470     REPEAT
2480        I=I+1
2490        ENTER @Path,I;Ws,Date,Ipcp,Pcp
2500        IF Pcp>0 THEN
2510           Raindepth=Pcp
2520        END IF
2530        IF Ws=9 THEN GOTO 2590
2540        IF Ipcp>Ipcpmax THEN
2550           Ipcpmax=Ipcp
2560        END IF
2570        Saveip=I
2580     UNTIL Date>=Enddate

         !Set scale for Y-axis precipitation

2590     IF Ipcpmax<=2 THEN
2600        Ipcpmax=2
2610        Pscale=40
2620     END IF
2630     IF Cfsmax<.1 THEN GOTO 6010  !Skip small storms

         !2640 - 3600 Draws and labels the axes, plots the actual
         hydrograph, and plots the rainfall hyetograph

2640     GINIT
2650     GRAPHICS ON
2660     DEG
2670     MOVE 5,34
2680     LDIR 90
2690     CSIZE 4
2700     LABEL "STREAMFLOW (CFS)"
2710     MOVE 60,1
2720     LDIR 0
2730     CSIZE 4
2740     LABEL "DAY OF MONTH"
2750     MOVE 12,74
2760     LDIR 270
2770     CSIZE 4
2780     LABEL "PRECIPITATION (IN)"
2790     MOVE 3,94
2800     LDIR 0
```

```
2810      CSIZE 4
2820      LABEL USING 2830;Ws,M1,D1,Hr1,Min1,M2,D2,Y2,Hr2,Min2
2830      IMAGE "WATERSHED #",Z," STORM HYDROGRAPH",ZZ,"/",ZZ,":",ZZ,ZZ,
   "-",ZZ,"/",ZZ,"/",ZZ,":",ZZ,ZZ
2840      CSIZE 3
2850      FOR T=D1 TO Tmax
2860         Td=18+(T-D1)*Tscale
2870         MOVE Td,6
2880         IF M1=10 OR M1=12 OR M1=1 OR M1=3 OR M1=5 OR M1=7 OR
   M1=8 THEN
2890            Monthday=31
2900         END IF
2910         IF M1=11 OR M1=4 OR M1=6 OR M1=9 THEN
2920            Monthday=30
2930         END IF
2940         IF M1=2 THEN
2950            Monthday=28
2960         END IF
2970         IF M1=2 AND Y1=80 OR Y1=84 OR Y1=88 OR Y1=92 THEN
2980            Monthday=29
2990         END IF
3000         IF T>Monthday THEN GOTO 3030
3010         LABEL T
3020         GOTO 3060
3030         T=T-Monthday
3040         LABEL T
3050         T=T+Monthday
3060      NEXT T
3070      FOR Cfs=0 TO Qmax
3090         MOVE 7,Qd
3100         LABEL Cfs
3110      NEXT Cfs
3120      FOR Ipcp=0 TO Ipcpmax
3130         Id=90-Ipcp*Pscale
3140         MOVE 16,Id
3150         LABEL Ipcp
3160      NEXT Ipcp
3170      CLIP 20,133,12,92
3180      AXES 2,2,20,12,6,5,2
3190      FRAME
3200      I=I1
3210      ENTER @Route,I;Ws,Date,Cfs
3220      Cfs=Cfs*Qscale+12
3230      Firdate=Date-Begdate
3240      Firdate=Firdate*Tscale+20
3250      MOVE Firdate,Cfs
3260      I=I-1
3270      REPEAT
3280         I=I+1
3290         ENTER @Route,I;Ws,Date,Cfs
3300         IF Ws=9 THEN GOTO 3380
3310         Outdate=Date
```

```
3320       Cfs=Cfs*Qscale+12
3330       Datel=Date-Begdate
3340       Datel=Datel*Tscale+20
3350       DRAW Datel,Cfs
3360       IF Enddate=Outdate THEN GOTO 3380
3370    UNTIL Date>=Enddate
3380    I=I2-1
3390    MOVE 1,1
3400    REPEAT
3410       MOVE 20,92
3420       I=I+1
3430       ENTER @Path,I;Ws,Date,Ipcp,Pcp
3440       IF Ws=9 THEN GOTO 3610
3450       IF Date>=Enddate THEN GOTO 3590
3460       I=I+1
3470       ENTER @Path,I;Ws1,Date1,Ipcp1,Pcp1
3480       IF Ws=9 THEN GOTO 3610
3490       IF Ipcp1=0 THEN GOTO 3590
3500       Ipcp=92-Ipcp1*Pscale
3510       Datel=Date-Begdate
3520       Date11=Date1-Begdate
3530       Datel=Datel*Tscale+20
3540       Date11=Date11*Tscale+20
3550       DRAW Datel,92
3560       DRAW Datel,Ipcp
3570       DRAW Date11,Ipcp
3580       DRAW Date11,92
3590       I=I-1
3600    UNTIL Date>=Enddate

        !Start of actual stormflow prediction equations

3610    Sm(9)=Sm0
3620    Sat=7.5 !Soil saturation value
3630    Gwl(9)=Gwl0
3640    Fi=2.0  !Infiltration rate, inches/15 minutes
3650    K=10    !So routing will work (no negative matrix values)
3660    I=I2-1

        !P(*) is the time matrix for all predicted values

3670    REPEAT
3680       I=I+1
3690       ENTER @Path,I;Ws,Date,Ipcp,Pcp
3700       IF Ws=9 THEN GOTO 4260
3710       IF K=10 THEN
3720          P(K-1)=Begdate
3730       END IF
3740       IF Pcp=0 THEN
3750          P(K)=P(K-1)+(15/1440)) !Add 15 minutes for next loop
3760          Ipcp=0
3770          GOTO 3810
```

```
3780         ELSE
3790            P(K)=Date
3800         END IF
3810         C=(P(K-1)+(15/1440))
3820         IF P(K)>C THEN
3830            P(K)=P(K-1)+(15/1440))
3840            Ipcp=0
3850            I=I-1
3860         END IF
3870         IF Sm(K-1)<Achplimit THEN GOTO 3900
3880         Qchp(K)=Ipcp*Achp    !Calc channel precipitation
3890         Ipcp=Ipcp*(1-Ipcp)
3900         IF Ipcp>Fi THEN
3910            Qxs(K)=Ipcp-Fi !Overland flow from excess prec rate
3920            Z=Fi
3930         END IF
3940         IF Ipcp<Fi THEN
3950            Qxs(K)=0
3960            Z=Ipcp
3970         END IF
3980         Sm(K)=Sm(K-1)+Z    !Add prec (Z) to soil moisture storage
3990         IF Sm(K)>Sat THEN
4000            Qof(K)=Sm(K)-Sat !Overland flow,exceeded soil retention
4010            Sm(K)=Sm(K)-Qof(K)
4020         END IF
4030         IF Sm(K)<Sat THEN
4040            Qof(K)=0
4050         ENDIF
4060         IF Sm(K)<=Fc THEN
4070            Qf(K)=0
4080            Q2=0
4090            Gwl(K)=Gwl(K-1)+Q2
4100            Qgw(K)=Gwl(K)*Agw !Calc of groundwater flow
4110            Gwl(K)=Gwl(K)-Qgw(K)
4120            IF Gwl(K)<0 THEN Gwl(K)=0
4130         END IF
4140         IF Sm(K)>Fc THEN
4150            Qf(K)=Fqf*(Sm(K)-Fc) !Calc of interflow
4160            Q2=Fk*(Sm(K)-Fc) !Calc of percolation
4170            Gwl(K)=Gwl(K-1)+Q2
4180            Qgw(K)=Gwl(K)*Agw  !Calc of groundwater
4190            Gwl(K)=Gwl(K)-Qgw(K)
4200            IF Gwl(K)<0 THEN Gwl(K)=0
4210         END IF
4220         Sm(K)=Sm(K)-(Qf(K)+Q2) !Reduction of soil moisture from flow
4230         IF Sm(K)<0 THEN Sm(K)=0
4240         K=K+1
4250      UNTIL Date>=Enddate
```

!When all precipitation has been input the model continues for 24 hours with no inputs. Lines 4260 - 4590

```
4260      T=K
4270      Date=P(K-1)
4280      FOR W=Date TO Enddate STEP (15*(1/1440))
4290         P(T)=W
4300         Ipcp=0
4310         Z=Ipcp
4320         Sm(T)=Sm(T-1)+Z
4330         IF Sm(T)>Sat THEN
4340            Qof(T)=Sm(T)-Sat
4350            Sm(T)=Sm(T)-Qof(T)
4360         END IF
4370         IF Sm(T)<Sat THEN
4380            Qof(T)=0
4390         END IF
4400         IF Sm(T)<=Fc THEN
4410            Qf(T)=0
4420            Q2=0
4430            Gwl(T)=Gwl(T-1)+Q2
4440            Qgw(T)=Gwl(T)*Agw
4450            Gwl(T)=Gwl(T)-Qgw(T)
4460            IF Gwl(T)<0 THEN Gwl(T)=0
4470         END IF
4480         IF Sm(T)>Fc THEN
4490            Qf(T)=Fqf*(Sm(T)-Fc)
4500            Q2=Fk*(Sm(T)-Fc)
4510            Gwl(T)=Gwl(T-1)+Q2
4520            Qgw(T)=Gwl(T)*Agw
4530            Gwl(T)=Gwl(T)-Qgw(T)
4540            IF Gwl(T)<0 THEN Gwl(T)=0
4550         END IF
4560         Sm(T)=Sm(T)-(Qf(T)+Q2)
4570         IF Sm(T)<0 THEN Sm(T)=0
4580         T=T+1
4590      NEXT W
4600      Ipcp=0.
4610      Rqmax=0
4620      FOR O=1 TO (T-1) STEP 1
4630         IF O=1 OR O=2 OR O=3 OR O=4 OR O=5 OR O=6 OR O=7 OR O=8 OR
   O=9 THEN
4640            Q(O)=0
4650            Qcf(O)=0
4660            Rq(O)=0
4670         ELSE
4680            Q(O)=(Qxs(O)+Qof(O)+Qf(O)+Qchp(O)+Qgw(O))
4690            Qcf(O)=(Q(O)/12)*939.928 !Convert area inches to cfs
4700         END IF
4710         IF O>9 THEN

               !Routing function

4720            Rq(O)=((Qcf(O)*Ddd)+(Qcf(O-1)*E)+(Qcf(O-2)*G)+
   (Qcf(O-3)*Hhh)+(Qcf(O-4)*J)+(Qcf(O-5)*Dd)+(Qcf(O-6)*Ee)+(Qcf(O-7)*Gg)
```

```
 +(Qcf(O-8)*Hh)+(Qcf(O-9)*Jj))
4730            IF Rq(O)>Rqmax THEN
4740               Rqmax=Rq(O)
4750            END IF
4760         END IF
4770      NEXT O
4780      FOR L=1 TO 470
4790         Qcf(L)=0
4800      NEXT L
4810      I=I1
4820      ENTER @Route,I;Ws,Date,Cfs
4830      Cfs=Cfs*Qscale+12
4840      Firdate=Date-Begdate
4850      Firdate=Firdate*Tscale+20
4860      MOVE Firdate,Cfs
4870      I=I-1
4880      W=1
4890      REPEAT
4900         I=I+1
4910         ENTER @Route,I;Ws,Date,Cfs
4920         IF Ws=9 THEN GOTO 4990
4930         Fd(W)=Date
4940         Qcf(W)=Cfs
4950         W=W+1
4960         Outdate=Date
4970         IF Enddate=Outdate THEN GOTO 4990
4980      UNTIL Date>=Enddate
4990      I=9
5000      LINE TYPE 4

          !Draw the predicted stormflow hydrograph

5010      REPEAT
5020         Date=P(I)
5030         Outdate=Date
5040         Cfs=Rq(I)*Qscale+12
5050         Datel=Date-Begdate
5060         Datel=Datel*Tscale+20
5070         IF Datel<=0 THEN GOTO 5130
5080         DRAW Datel,Cfs
5090         I=I+1
5100      UNTIL Date>=Enddate

          !Lines 5110 - 5420 calculate predicted and actual flow volume
          totals

5110      Rfd=0
5130      Realflowsum=0
5140      Predflowsum=0
5150      A=1
5160      B=8
5170      C=1
```

```
5180    Rfd=DROUND(Fd(A),5) DIV (1/100)
5190    Pfd=DROUND(P(B),5) DIV (1/100)
5200    IF Rfd=Pfd THEN
5210       Realflowsum=Realflowsum+Qcf(A)
5220       Predflowsum=Predflowsum+Rq(B)
5230       A=A+1
5240       IF Fd(A)=-1 OR A=470 THEN GOTO 5430
5250       IF Fd(A)=0 THEN GOTO 5180
5260       B=B+1
5270       C=C+1
5290    ELSE
5300       IF Rfd<Pfd THEN
5310          A=A+1
5320          GOTO 5420
5330       END IF
5340       Rfd=DROUND(Fd(A),5) DIV (1/100)
5350       Pfd=DROUND(P(B),5) DIV (1/100)
5360       IF Fd(A)>=Enddate THEN GOTO5430
5370       IF Fd(A)=-1 THEN GOTO 5430
5380       IF Rfd=Pfd THEN GOTO 5420
5390       B=B+1
5400       IF P(B)<=0 THEN GOTO5430
5410    END IF
5420    IF P(B-1)<>Enddate THEN GOTO 5180

        !Rest of program formats and prints output values

5430    LINE TYPE 1
5440    Dqmax2=(Cfsmax-Rqmax)
5450    LDIR 0
5460    CSIZE 4
5470    LORG 8
5480    MOVE 130,85
5490    LABEL USING 5500;Predflowsum
5500    IMAGE "PREDICTED FLOW SUM=",DDDDDD.DDDDDD
5510    MOVE 130,80
5520    LABEL USING 5530;Realflowsum
5530    IMAGE "REAL FLOW SUM=",DDDDDD.DDDDDD
5550    CSIZE 5
5560    LABEL USING 5570;Dqmax2
5570    IMAGE "QR-QP=",DDDDD.DDDD
5580    MOVE 130,70
5590    CSIZE 4
5600    LABEL USING 5610;A,B,C
5610    IMAGE "A=",DDDD,2X,"B=",DDDD,2X,"C=",DDDD
5620    MOVE 130,65
5630    LABEL USING 5640;Stnum
5640    IMAGE "STORM NUMBER",1X,DDD
5650    GOTO 5750
5660    INPUT "PRINT OUT? YES=Y NO=N",Choice$
5670    IF Choice$="Y" THEN
5680       PRINTER IS 701
```

```
5690        PRINT CHR$(12)
5700        PRINTER IS 1
5710        DUMP DEVICE IS 701,EXPANDED
5720        DUMP GRAPHICS
5730        Choice$="N"
5740     END IF
5750     GCLEAR
5760     PRINTER IS 701
5770     PRINT "STNUM=",Stnum
5780     PRINT "ENDING SM=",Sm(T-1)
5790     PRINT "REAL QMAX=",Cfsmax
5800     PRINT "PRED QMAX=",Rqmax
5810     PRINT "QR-QP=",Dqmax2
5820     Sqres=Sqres+Dqmax2^2
5830     PRINT"SQUARE RESIDUAL OF PEAKS=",Sqres
5840     IF Cfsmax>0 THEN
5850        Percent2=100-((Dqmax2/Cfsmax)*100)
5860        PRINT "PERCENT PREDICTED VS. REAL=",Percent2
5870     END IF
5880     PRINT "REAL FLOW SUM=",Realflowsum
5890     PRINT "PRED FLOW SUM=",Predflowsum
5900     PRINT "RFS-PFS=",(Realflowsum-Predflowsum)
5910     Sqres1=Sqres1+(Realflowsum-Predflowsum)^2
5920     PRINT "SQUARE RESIDUAL OF VOLUME=",Sqres1
5930     IF Realflowsum>0 THEN
5940        Percent1=100-((Realflowsum-Predflowsum)/Realflowsum)*100
5950        PRINT "PERCENT PRED VS REAL=",Percent1
5960     END IF
5970     PRINT"A=",A,"B=",B,"C=",C
5980     PRINT "RAINDEPTH=",Raindepth
5990     PRINT
6000     PRINT
6010     PRINTER IS 1
6020     GCLEAR
6030     GOTO 330
6040     END
```

APPENDIX B

PRECIPITATION INCREMENTING PROGRAM LISTING

Precipitation Incremeting Program

Overview

The program operates with two main loops, one to establish the beginning time of a storm and the second to segment the storm into 15 minute intervals.

Initialization of array "UPCP" with dimensions large enough to allow for four days of 15 minute increments is done on line 10. All loop counters initialized in the top eight lines are one time values. Lines 120 - 140 are reset for each storm (when the large loop occurs). Input for the beginning of a storm occurs at line 160. Input consists of watershed number, month, day, year, hour, minute, total precipitation up to that time (zero for storm beginning), and a scalar date. In this program only the scalar date is used for any calcualtions. Similiar inputs are requested in line 340. "I" is increased by one before each input statement to read the next data file, thus the interval between the two dates is used in calculating precipitation increments.

Line 440 checks for the end-of-file flag (Ws=9) that is or must be included in all data files. Line 450 is the start of the small loop that calculates the increments within a single storm. A check is made in this line to determine if the precipitation total (PCP) is zero which would indicate another storm has started. If PCP is not zero then the loop calculates interval time and increase in precipitation, divides this data into one minute segments, and stores it in the array "UPCP". Then the program makes a short loop up to the input at line 310 and repeats the above steps until PCP = 0 (new storm).

If PCP does equal zero at line 450 then the program loop drops to line 610 and sets the input counter "I" back one, since "I" is increased by one at the next input. Line 650 calculates "Z", the number of 15 minute increments within each storm. Line 660 adds one extra step for storms that do not come out to even 15 minutes intervals. Line 670 is for storms that are shorter than 15 minutes in duration. The value "Z" indicates how many times the program cycles through lines 680 - 1040. These lines sum 15 one minute incremented data into one 15 minute segment and stores the date, incremental precipitation, and sum of precipitation up to that time (line 1030).

When the entire storm has been incremented into 15 minute intervals, the program clears the array at line 1100, goes back to line 100, and begins input of a new storm. Line 1150 is called from line 440 to store the end-of-file mark (Ws=9) that is used in other watershed programs, and in the Clayton model.

```
1          !PROGRAMMER:Ron McCormick. Fall, 1985
2          !
10         DIM Upcp(20000)
20         Loopc=1
30         PRINTER IS 1
40         Icp=0
50         Ic=0
60         Fi=1
70         I=0
80         Ipcp=0
90         Fname$="PCP18384"
100        MASS STORAGE IS":HP8290X,700,0"
110        ASSIGN @Path TO Fname$
120        Icp=0
130        Ic=0
140        Loopc=0
150        I=I+1
160        ENTER @Path,I;Ws,M,D,Y,Hr,Mn,Pcp,Date
170        M1=M
180        D1=D
190        Y1=Y
200        Hr1=Hr
210        Mn1=Mn
220        Pcp1=Pcp
230        Date1=Date
240        Fm=M
250        Fd=D
260        Fy=Y
270        Fhr=Hr
280        Fmn=Mn
290        Fpcp=Pcp
300        Fdate=Date
305        IF Pcp=9.99 THEN GOTO 100
310        I=I+1
340        ENTER @Path,I;Wss,Mm,Dd,Yy,Hrr,Mnn,Pcpp,Datee
350        Ws=Wss
360        M2=Mm
370        D2=Dd
380        Y2=Yy
390        Hr2=Hrr
400        Mn2=Mnn
410        Pcp2=Pcpp
420        Date2=Datee
430    !START OF PRECIPITATION INCREMENT LOOP
440        IF Ws=9 THEN GOTO 1141
450        IF Pcp2>0 AND Pcp2<9.8 THEN
460           Pc=Pcp2-Pcp1
480           Itime=INT((Date2-Date1)/(1/1440))
510           Ipcp=Pc/Itime
520           FOR Ix=Ic TO Ic+(Itime)
530              Upcp(Ix)=Ipcp
540           NEXT Ix
```

```
550         Ix=Ix-1
560         Ic=Ix
570         Date1=Date2
580         Pcp1=Pcp2
590         GOTO 310
600      END IF
610      I=I-1
650      Z=INT((Date1-Fdate)/(15*(1/1440)))
660      IF ((Date1-Fdate) MOD(15*(1/1440)))>.0010 THEN Z=Z+1
670      IF Z=0 THEN Z=1
680      FOR X=Fi TO Fi+Z
690         IF X=Fi THEN
700            Actualp=0
710            GOTO 890
720         END IF
730         Actualp=0
750         IF (Ix-Icp)<15 AND (Ix-Icp)>=0 THEN
760            FOR Icp=Loopc TO Loopc+(Ix-Icp)
770               Actualp=Actualp+Upcp(Icp)
780            NEXT Icp
790         END IF
800         IF (Ix-Icp)>=15 THEN
810            FOR Icp=Loopc TO Loopc+14
820               Actualp=Actualp+Upcp(Icp)
830            NEXT Icp
840         END IF
860         Icp=Icp
870         Loopc=Icp
880         Su=Su+Actualp
890         IF X=Fi THEN
900            Date=Fdate
910         ELSE
920            Date=Date+(15*(1/1440))
930         END IF
990         PRINT X,Ws,Date,Actualp,Su
1000        Fname$="PCP18384I"
1010        MASS STORAGE IS ":HP8290X,700,1"
1020        ASSIGN @Route TO Fname$
1030        OUTPUT @Route,X;Ws,Date,Actualp,Su
1040     NEXT X
1050     Fi=X
1060     PRINT
1070     PRINT
1080     PRINTER IS 1
1090     Fname$="PCP18384"
1100     FOR S=1 TO 20000
1110        Upcp(S)=0
1120     NEXT S
1130     Su=0
1135     PRINT"MONTH/DAY",M1,"/",D1
1140     GOTO 100
1150     Ws=9
```

```
1160      Date=-1
1170      Pcp=0
1180      Su=0
1190      Fname$="PCP18384I"
1200      MASS STORAGE IS ":HP8290X,700,1"
1210      ASSIGN @RouteTO Fname$
1220      OUTPUT @Route,X;Ws,Date,Pcp,Su
1230      Elapsed=TIMEDATE MOD 86400
1240      Hours=Elapsed/60/60
1250      PRINT"HOURS=",Hours
1260      END
```

APPENDIX C

STREAMFLOW INCREMENTING PROGRAM LISTING

Streamflow Incrementing Program

Overview

The program operates by reading a (15 minute precipitation) date (line 190) from a file created by the precipitation incrementing program, then reading an un-incremented streamflow file until it reaches a date that is equal to or greater that the precipitation date. The program then saves all those streamflow dates that are less than the precipitation date.

Once the program finds a date that is greater than the precipitation date read in line 190, it operates in much the same way as the precipitation incrementing program in that there is now an interval in which to divide the data into 15 minute increments. The main difference is the streamflow incrementing program creates streamflow data points only on dates that directly correspond to precipitation dates.

Line 180 starts the main loop that will read each individal precipitation date from existing incremented precipitation data. Lines 200 - 210 check to see if the precipitation date is still less than the last stored date. If it is, then there are still intervals in the streamflow file needing incrementation and the program jumps to lines 440 - 750 to do this. Allowing for either rising or falling limbs of the hydrograph lines 440 - 750 calculate data points in the same manner as described in the precipitation program overview.

If the new precipitation date is greater than or equal to the last stored streamflow date then the program (lines 220 - 250) saves that flow date in an array and starts reading new flow dates (lines 260 - 320) until a flow date is greater than the current precipitation date, again storing all flow dates between.

Output involves two steps. In the first step the number of incremented precipitation records plus the number flow records calculated is determined. This number is the value for the loop counter K (lines 820 - 860). This loop outputs all the incremented streamflow data calculated by the program to a file. This file must be large enough to contain the number of records (K). To determine K, add the record number of incremented precipitation records to the number of flow records created by the incrementing program. If streamflow dates exist after the last precipitation date (they will not be incremented or read by the program) then the second step in the output reads the extra streamflow data and outputs those records to the file to complete the year of record (lines 870 - 921).

```
1        !PROGRAMMER:Ron McCormick, Fall, 1985
2        !
10       DIM Fate(4000),Cfs(4000)
20       S=1
30       Datef1=0
40       Q1=0
50       PRINT "PUT OLD PREC AND FLOW IN 1, NEW FLOW IN 0"
60       PAUSE
70       P=0
80       R=1
90       F=0
100      Incq=0
110      Fname$="PCP17879I"
120      Flow$="WS17879"
130      Flux$="WS17879I"
140      MASS STORAGE IS ":HP8290X,700,1"
150      ASSIGN @Path TOFname$
160      MASS STORAGE IS ":HP8290X,700,1"
170      ASSIGN @Route TO Flow$
180      FOR P=1 TO 2708
190         ENTER @Path,P;Ws1,Date,Pcp,Sum
200         IF Date<Datef1 THEN
210            GOTO 440
220         ELSE
230            Fate(R-1)=Datef1
240            Cfs(R-1)=Q1
250         END IF
260         REPEAT
270            F=F+1
280            ENTER @Route,F;Ws,M,D,Y,H,Mn,Stage,Datef,Q
290            Fate(R)=Datef
300            Cfs(R)=Q
301            IF Ws=9 THEN GOTO 760
310            R=R+1
320         UNTIL Datef>=Date
350         Datef=Fate(R-2)
351         Q=Cfs(R-2)
361         Datef1=Fate(R-1)
371         Q1=Cfs(R-1)
380         Itime=INT((Datef1-Datef)/(1/1440))
390         Iq=ABS(Q1-Q)
400         Incq=Iq/Itime
440         IF Iq=0 THEN
450            Cfs(R-1)=Q
451            Fate(R-1)=Date
460            GOTO 610
470         END IF
480         IF Q1>=Q THEN
481            Cfs(R-1)=Cfs(R-2)
490            FOR Ix=Datef TO Date STEP (1/1440)
500               Cfs(R-1)=Cfs(R-1)+Incq
510            NEXT Ix
```

```
520            END IF
530            IF Q1<Q THEN
531              Cfs(R-1)=Cfs(R-2)
540               FOR Ix=Datef TO Date STEP (1/1440)
550                  Cfs(R-1)=Cfs(R-1)-Incq
560               NEXT Ix
570            END IF
580            Fate(R-1)=Date
610            Datef=Fate(R-1)
620            Q=Cfs(R-1)
670            R=R+1
750         NEXT P
760         Ws=1
820         FOR K=1 TO 3058
830         MASS STORAGE IS ":HP8290X,700,0"
840            ASSIGN @Walk TO Flux$
850            OUTPUT @Walk,K;Ws,Fate(K),Cfs(K)
860         NEXT K
861         T=3059
870         FOR Z=1479 TO 1627
871            ENTER @Route,Z;Ws,M,D,Y,H,Mn,Stage,Datef,Q
872            Fate(T)=Datef
873            Cfs(T)=Q
890            T=T+1
900         NEXT Z
901         Ws=1
910         FOR K=3059 TO 3206
911            IF K=3206 THEN Ws=9
920            OUTPUT @Walk,K;Ws,Fate(K),Cfs(K)
921         NEXT K
930         Elapsed=TIMEDATE MOD 86400
940         Hours=Elapsed/60/60
950         PRINT "HOURS=",Hours
960         END
```

VITA

Ronald Joseph McCormick

Candidate for the Degree of

Master of Science

Thesis: A LUMPED, DETERMINISTIC RAINFALL-RUNOFF MODEL FOR SMALL, FORESTED WATERSHEDS IN SOUTHEASTERN OKLAHOMA

Major Field: Forest Resources

Professional Organizations: American Water Resources Association; Soil Conservation Society of America.

Biographical:

Personal Data: Born in Belding, Michigan, December 22, 1959, the son of John and Rosemary McCormick.

Education: Graduated from Belding High School, Belding, Michigan, in May, 1978; received Bachelor of Science Degree in Forestry from Michigan Technological University in May, 1983; completed requirements for the Masters of Science degree at Oklahoma State University in July, 1986.

Professional Experience: Teaching Assistant, Department of Forestry, Michigan Technological University, Summer, 1981; Research Assistant, Department of Forestry, Michigan Technological University, Ford Forestry Research Center, Alberta, Michigan, Summer, 1982; Research Assistant, Department of Forestry, Oklahoma State University, July, 1984, to May, 1986.