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## An Application of the Utah State University Watershed Simulation Model to the Entiat Experimental Watershed, Washington State

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**AN APPLICATION OF THE UTAH STATE UNIVERSITY WATERSHED  
SIMULATION MODEL TO THE ENTIAT EXPERIMENTAL  
WATERSHED, WASHINGTON STATE**

**by**

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and  
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**Prepared for**

**Forest Service  
U.S. Department of Agriculture  
Pacific Northwest Forest and Range Experiment Station  
Portland, Oregon**

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**October 1975**

**PRWG126-1**



## **ABSTRACT**

To study the effects of a forest fire on runoff characteristics, the Utah State University Watershed Simulation Model (USUWSM) has been applied to three small drainage areas in the Entiat Experimental Watershed which is located within the Wenatchee National Forest of central Washington. Each component of the USUWSM has been described in the report, including structural changes to the model that were necessary to achieve reasonable agreement between observed and simulated runoff hydrographs. Lack of information on the spatial distribution of precipitation due to the absence of an adequate precipitation gaging network on or close to the study area was a severe handicap to the simulation study. Only a very short period of post-fire streamflow record was available and thus it was possible to make only qualitative conclusions regarding the effects of the forest fire on runoff characteristics.

**Keywords:** Computer models, Forest-fires, Forest management, Hydrologic models, Mathematical models, Mountain forests, Simulation, Small watersheds, Streamflow, Watershed management, Water yield

## ACKNOWLEDGMENTS

This publication represents the final report of a project which was supported primarily with funds provided by the Forest Hydrology Laboratory, Wenatchee, Washington. This laboratory is a part of the Pacific Northwest Forest and Range Experiment Station of the United States Forest Service. The work was accomplished by personnel of the Utah Water Research Laboratory (UWRL) in accordance with a contract which was signed by officials of both Utah State University and the U.S. Forest Service.

Many people assisted with the acquisition of needed data, and provided constructive comments and suggestions throughout the course of this study. Special thanks are extended to Mr. David Helvey of the Forest Hydrology Laboratory in Wenatchee both for the data which he supplied and for his constructive comments and suggestions throughout the course of the entire study, including a careful review of the report manuscript. Gratitude also is expressed to Dr. Richard H. Hawkins and Mr. Eugene K. Israelsen for their constructive reviews of the manuscript.

David S. Bowles  
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George B. Shih

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## PARTIAL LIST OF SYMBOLS

<u>Symbol</u>	<u>Definition</u>
A	albedo or reflectivity of the snowpack surface
AE	absolute error in prediction of daily runoff for one year
AV	actual evapotranspiration
BF	baseflow
CP(m)	evapotranspiration per °F of mean monthly temperature for the m <sup>th</sup> month
D(m)	the number of days in the m <sup>th</sup> month
EP	potential evapotranspiration
ER	error in prediction of annual streamflow
ET	evapotranspiration
F, F'	freewater depth
$f_c$	equilibrium infiltration rate
$f_o$	incremental infiltration rate
G(0)	initial groundwater storage
G(t)	groundwater storage at time, t
$G_d$	sum of percolation and interflow
$G_s$	soil moisture above retention capacity
GWR	net withdrawal from the zone of percolation summed over one year
IF	interflow
$k_b$	proportion of AVSM that becomes baseflow
$k''_d$	proportion of $G_d$ that becomes interflow
$k'_d$	value of $k''_d$ approached as $M_s(t)$ approaches $M_{cs}$ from above; dependent on slope and relative magnitudes of vertical and horizontal permeability
$k_g$	decay constant for soil moisture excess treated as a linear reservoir

## PARTIAL LIST OF SYMBOLS (cont.)

<u>Symbol</u>	<u>Definition</u>
$k_i$	proportion of outflow from detention storage which becomes interflow
$k_m$	snowmelt coefficient
$k_s$	decay constant from surface runoff and channel precipitation depending upon the basin characteristics (channel precipitation)
$k_w$	proportion of soil moisture deficit made by withdrawal
LOSS	observed precipitation minus observed streamflow
$M_{cs}$	soil moisture retention capacity
$M_{es}$	soil moisture wilting point
$M_{rs}$	daily snowmelt amount in inches
$M_s(t)$	soil moisture storage
$M_{sn}(t)$	snowpack
$M_{ss}$	saturated soil moisture storage
$n$	number of days on which approximate moving average is based
$N_r$	interflow
$P_b$	total precipitation at Burns gage for the same period as is used in calculating $P_i$
$P_b'$	observed total precipitation at Burns gage for the contemporaneous period
$P_i$	total precipitation at the $i^{th}$ study area gage for the entire period of observed data at that gage
$P_i'$	estimated total precipitation at the $i^{th}$ study area gage for the contemporaneous period
PET	potential evapotranspiration
PPT	precipitation
$Q_i$	observed streamflow on $i^{th}$ day of year
$QP_i$	predicted streamflow on $i^{th}$ day of year

## PARTIAL LIST OF SYMBOLS (cont.)

<u>Symbol</u>	<u>Definition</u>
q	discharge rate from the reservoir
RF	runoff
RH	recharge to zone of percolation
RI	monthly radiation index for the study area
RN	rainfall
S(t)	storage within the basin at any time, t
SDAY	number of days since the last snowfall
$S_i$	interception storage capacity
$S_i(t)$	interception storage
SM	soil moisture storage
SMMA(t)	approximate moving average of soil moisture storage at time, t
SN	snowfall
SNGM	daily groundmelt from snowpack
SNRF	snow runoff volume
SR	surface runoff
STM	streamflow
$T_a$	mean daily temperature
TEM	average monthly air temperature
$T_m$	temperature at which snowmelt commences in °F
$T_r$	temperature above which all precipitation is treated as rain
$T_s$	temperature below which all precipitation is treated as snow
VR	variance
WD	withdrawal from zone of percolation
WHC	water holding capacity

## CHAPTER I

### INTRODUCTION

This study was performed for the Pacific Northwest Forest and Range Experiment Station of the United States Forest Service. The objective of the study was to model the hydrologic system of three small drainage areas in the Entiat Experimental Watershed in order to help understand effects on runoff characteristics resulting from management and other changes in the watershed. In particular, the ability of the model to predict these effects is demonstrated by simulating runoff hydrographs associated with pre-fire and post-fire conditions on the watershed.

When the experimental watersheds were first established, the Forest Service planned to investigate the effects of various management practices on streamflow. Two of the three watersheds were to have been subjected to various management practices while the third was to be left in its natural condition to act as a "control" area. Streamflow correlation relationships were established between the control watershed and each of the other two watersheds. As management practices were applied to the first two watersheds, the measured streamflow quantities were compared with the estimate of streamflows that would have occurred in the absence of management, the estimated quantities being obtained from the correlation relationships with the third watershed. In this way, changes in streamflows associated with particular management practices were estimated. However, on August 24, 1970, an uncontrolled forest fire swept across parts of the experimental watersheds, including the control area, and thus changed the emphasis of the study to one of investigating the effects of forest fires on streamflow.

Because the forest fire changed vegetation conditions on each of the three study areas, it no longer was possible to use the control watershed to predict runoff from the other two areas under virgin conditions. For this reason, hydrologic simulation was proposed as a technique for predicting the effect of the fire on the runoff characteristics of each of the three

study areas. In addition, it was considered that the development and application of a hydrologic simulation model would provide increased insight into (1) the basic hydrologic processes occurring within the study areas, and (2) additional data requirements to support further investigations.

To form a watershed hydrologic simulation model a collection of mathematical submodels, each representing basic physical processes in the hydrologic cycle (see Figure 1), are linked together by applying the concept of continuity of mass. This synthesis of the mathematical submodels into a dynamic model of the prototype system is achieved with the aid of a digital computer. The model transforms measured or estimated meteorologic inputs into predicted outflow functions from the watershed. When the model adequately represents the prototype system, the computed outflow closely resembles the observed outflow. Thus, the comparison between computed and observed streamflow provides a check on the adequacy of the model. Furthermore, the model can be applied to any other watershed containing the same major hydrologic processes by adjusting the model parameters to reflect the new watershed characteristics.

In this study the model was verified (calibrated and tested) using eight years of pre-fire data. During the verification stage, the model components were tested and improved to define the system as accurately as possible. The model then was run to represent the one year of post-fire conditions for which data were available. This run was accomplished by changing several of the model parameters to appropriate values based on observed post-fire conditions. When the same set of meteorological data were input to the model using firstly the pre-fire parameter set, and secondly the post-fire parameter set, the differences between the computed streamflow for these two runs provided an estimate of the effects of the forest fire on streamflow characteristics.

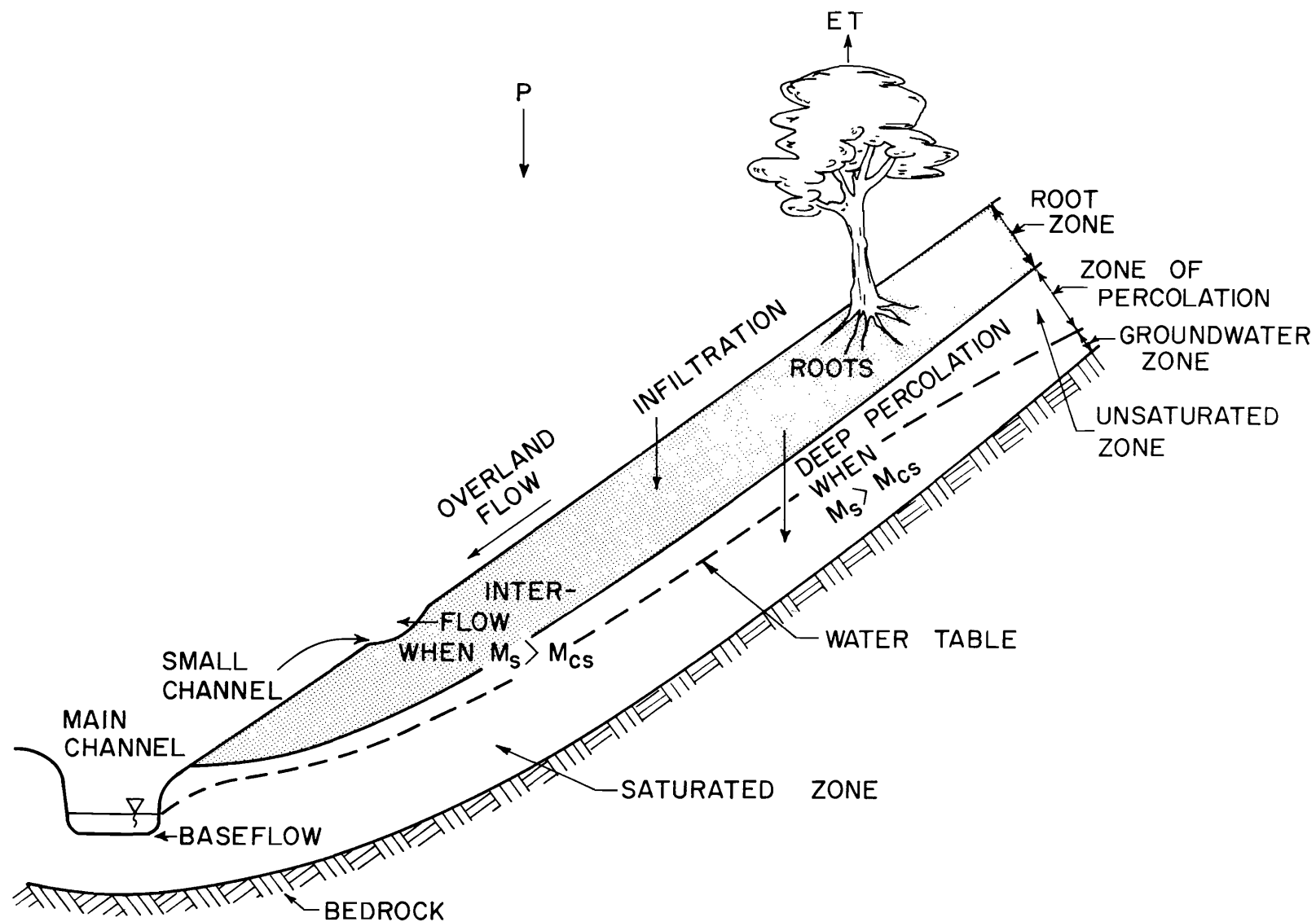


Figure 1. The terrestrial part of the hydrologic cycle in a steep mountain watershed as represented by original Utah State University Watershed Simulation Model (USUWSM).

## CHAPTER II

### THE STUDY AREA

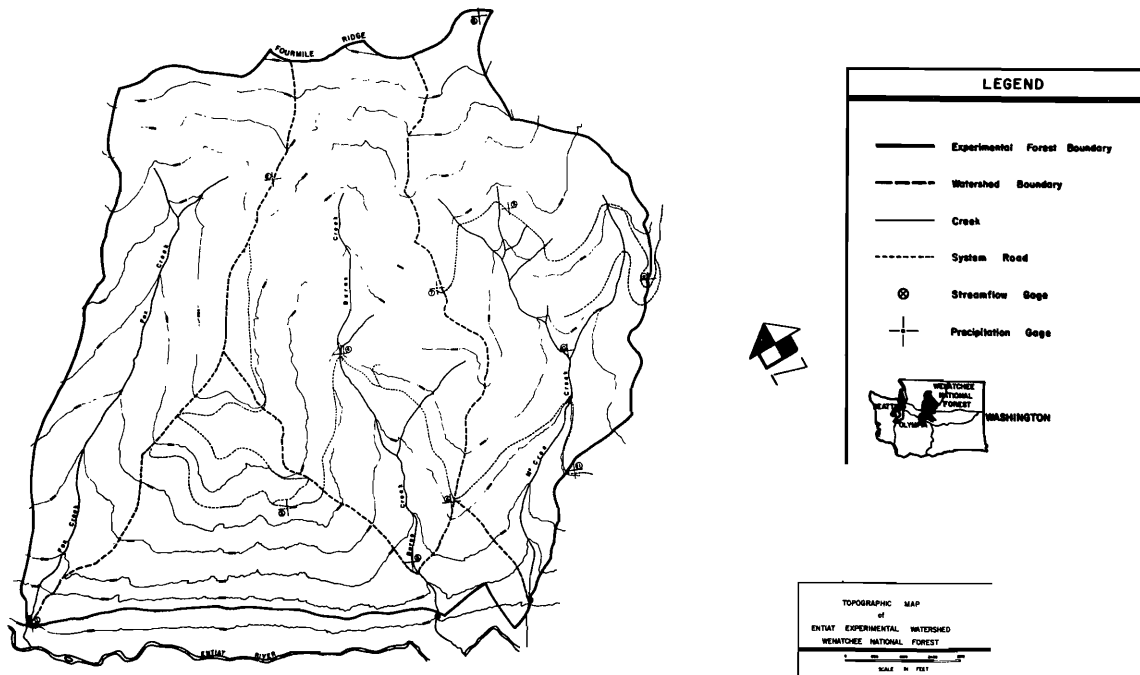
The Entiat Experimental Watershed is located about 50 miles (80 km) north of Wenatchee and is part of the Wenatchee National Forest in Washington State (see Figure 2 and Photos 1 and 2). The Entiat Experimental Watershed was set aside in 1957 as a study area representative of much of the forested lands east of the Washington Cascade Mountain crest (Berndt, 1967).

Three adjacent drainage areas within the experimental forest were simulated in this study. Each area is a hanging valley formed by glacial action and oriented in a general southwest direction between Four-mile Ridge, the northern watershed boundary, and the Entiat River (see Figure 2). The streams which drain these three areas are Fox, Burns, and McCree Creeks. Each watershed is approximately two square miles (3,200 ha) in area with elevations ranging from 2,000 feet (609.6 m) to 7,100 feet (2,164 m) and a mean slope of about 50 percent, but slopes as steep as 90 percent are common.

Klock (1971) describes the soils of the area as follows:

The base rock on the watersheds is an extensive formation known as the Chelan Batholith, a mesozoic intrusive granodiorite with biotite and hornblende as accessory minerals. A medium- to coarse-grained massive rock, the gray granodiorite weathers deeply where exposed. Since glaciation, the area has been periodically covered by volcanic ash and pumice, mostly originating from Glacier Peak (Fryxell, 1965) approximately 33 kilometers (21 miles) west-northwest of the study area.

The Choral soil series occupies about 55 percent of the area (Iritani and Meyer, 1967). Rampart soils occupy another 30 percent, and rock land or rock outcrops account for 15 percent. Choral soils are well drained, moderately coarse



**Figure 2. Topographical map of the three study watersheds in the Entiat Experimental Watershed (1 ft. = 0.305 m).**





**Photo 1. View of burnt study area.**



**Photo 2. View of burnt study area.**

textured, and derived from volcanic ash and pumice. The surface 60 centimeters (24 ins.) is a fine, sandy loam grading to coarse, loamy sand. This is underlain by pure pumice up to 6 meters (20 ft.) deep. Rampart soils are very similar to Choral except they occur at lower elevations and have developed under warmer climatic conditions.

Pre-fire vegetation also is described by Klock (1970):

Vegetation destroyed by the fire was almost entirely mature virgin forest. Ponderosa pine (*Pinus ponderosa* Laws.) was the main species with Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) as the main associated species. Stocking densities ranged from medium to poor. Common understory species were snowbrush ceanothus (*Ceanothus velutinus* Dougl.), bitterbrush (*Purshia tridentata* (Pursh) DC.), grouse whortleberry (*Vaccinium scoparium* Leib.), and pinegrass (*Calamagrostis rubescens* Buckl.).

Average annual precipitation for the entire study area was estimated to be about 28 inches (710 mm). Typically, about two-thirds of the annual precipitation is in the form of snow. With the exception of snowmelt flows, pre-fire streamflow remained remarkably uniform and was not very responsive to rainfall. This unresponsiveness of streamflow volumes to precipitation volumes is demonstrated at the annual level by

Figures 3, 4, and 5. For example, 1970 annual streamflow is only slightly different from 1963 annual streamflow, but 1963 annual precipitation is approximately four times the 1970 annual precipitation. The 1971 points on Figures 3, 4, and 5 represent the first year after the destruction of vegetation by wildfire, and demonstrate an increased responsiveness after the fire. At the daily level the unresponsiveness of observed streamflow to individual precipitation events can be observed from Figure 19.

Helvey (1973) has suggested that the streams are not very responsive to rainfall because summer storms are not large enough to satisfy moisture deficits in the soil water or rooting zone. Mean annual flows for the Fox, Burns, and McCree Creeks during the study period were 7.11 inches (181 mm), 6.08 inches (154 mm), and 4.27 inches (108 mm), respectively. Freezing temperatures persist for 5 months of each year. The annual mean temperature over the entire study area was estimated to be about 40°F (4.4°C).

The forest fire resulted from an intense dry lightening storm that swept across much of north-central Washington State during the early morning hours of August 24, 1975. Berndt (1971) describes the fire as "one of the most serious fire disasters ever to occur in the region. Ultimately, about 115,000 acres (284,000 ha) of timber were devastated in this single lightening-fire sequence. This area included the Entiat Experimental Forest where water yields, climate, and other environmental variables" had been studied for nearly 10 years on the three small watersheds.

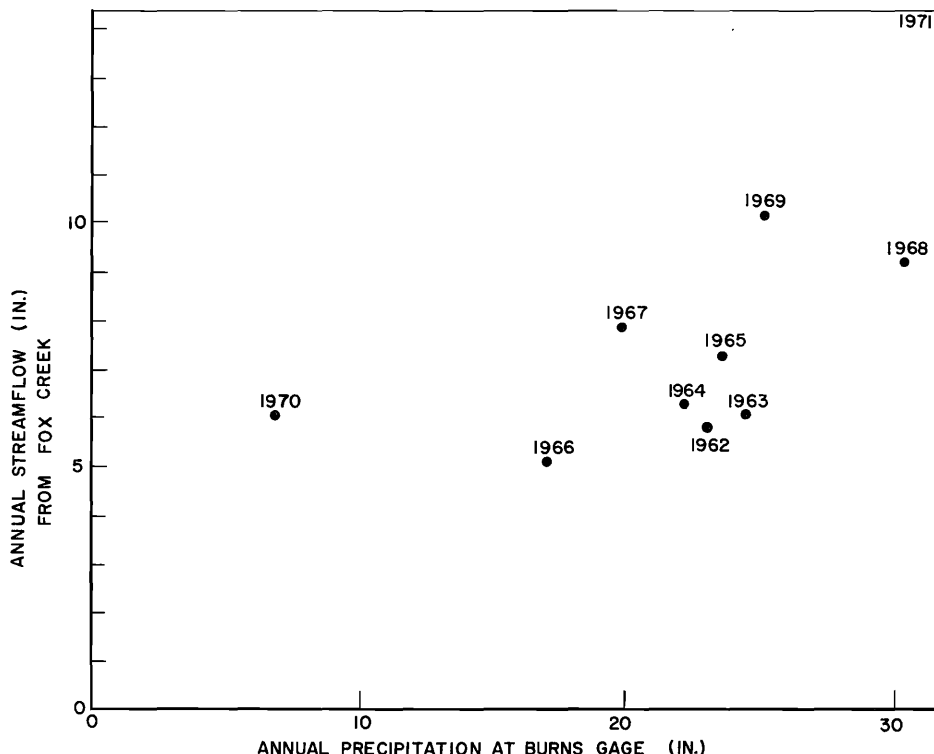


Figure 3. Annual streamflow from Fox Creek versus annual precipitation at Burns gage (1 in. = 25.4 mm).

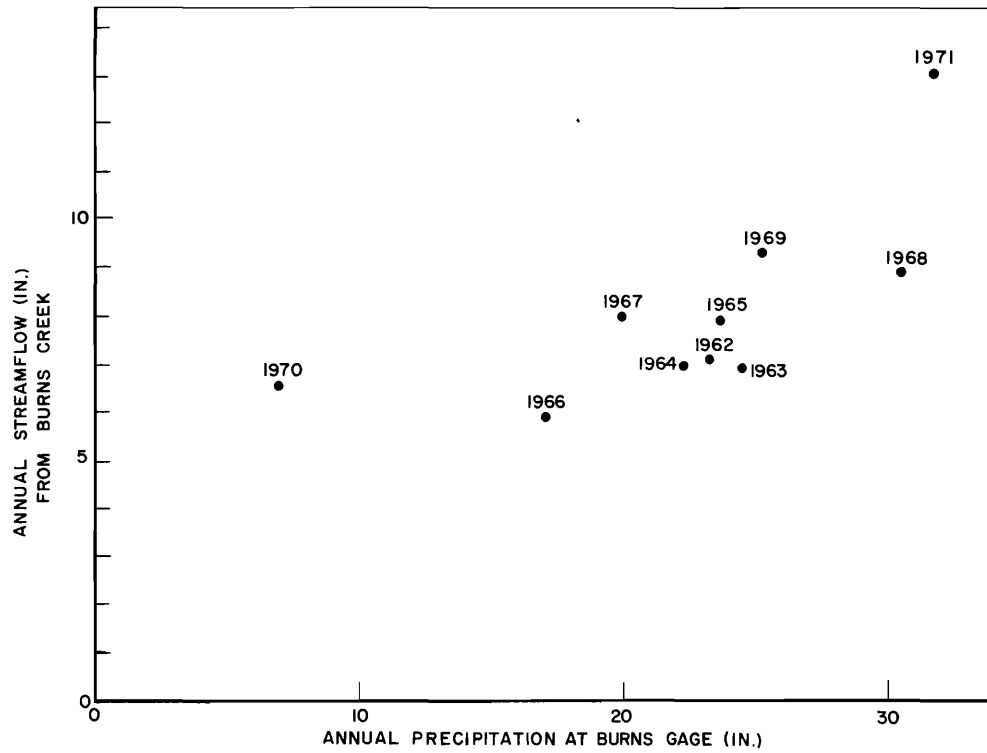


Figure 4. Annual streamflow from Burns Creek versus annual precipitation at Burn gage (1 in. = 25.4 mm).

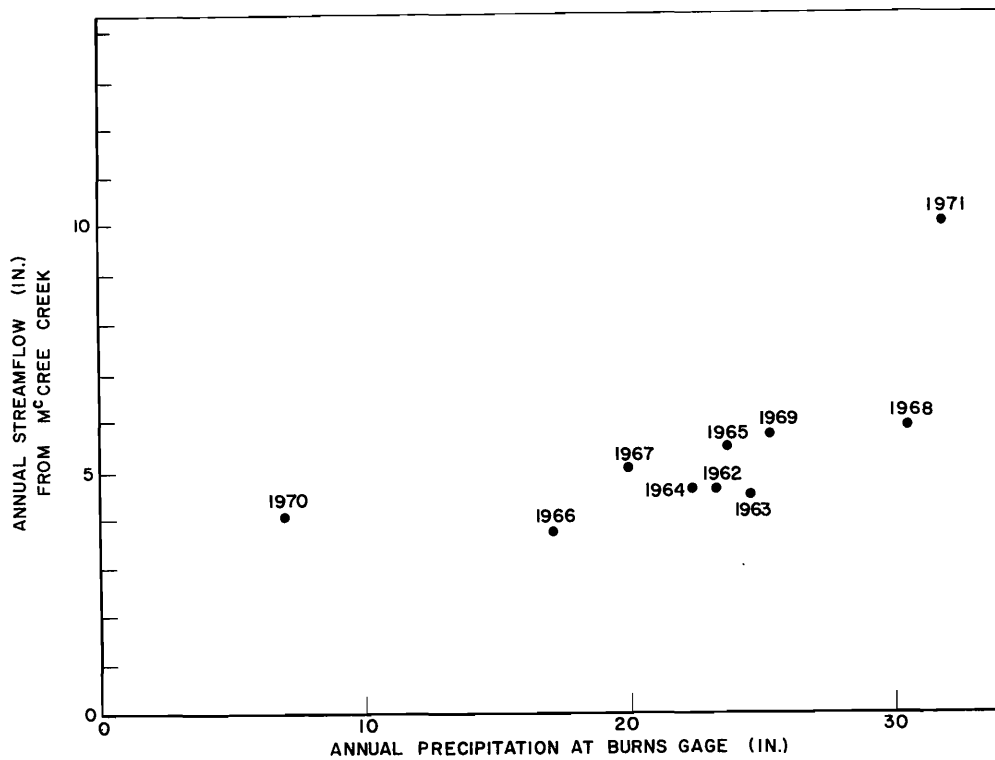


Figure 5. Annual streamflow from McCree Creek versus annual precipitation at Burns gage (1 in. = 25.4 mm).

## CHAPTER III

### DATA PREPARATION

The time increment for the Utah State University Watershed Simulation Model (USUWSM) is one day, and therefore daily data are required. Daily streamflow, precipitation, and temperature data were supplied by the U.S. Forest Service. Separate data were prepared for each of the three watersheds for a study period of nine years duration commencing on October 1, 1962. The preparation of each type of data is briefly described below.

#### Streamflow

Daily streamflow data in cubic feet per second were supplied on punched cards. These data for each watershed were converted from cubic feet per second to inches since USUWSM is written to accept streamflow data in inches.

#### Precipitation

There is only one precipitation gage in the study area with records covering the entire study period. This gage is located close to the downstream extremity of the Burns watershed. Runoff yield per unit area was computed for each watershed and the values obtained showed marked differences between watersheds. If it is assumed that pre-fire evapotranspiration characteristics for the three watersheds were fairly homogeneous, and that no important subsurface flows exist across the watershed boundaries, then the differences between the runoff ratios are due to differences in the amount of precipitation on each area. Following this reasoning, a basis was sought for the spatial distribution over the study area of precipitation measured at the single precipitation gage.

Precipitation records were available for two sets of gages. The first, which covered the complete study period, was comprised of the Burns station and six other stations on an approximate radius of 30 miles (48 km) from the experimental watershed (see Figure 6). The second data set consisted of nine stations situated on the study area (see Figure 2). These records were available for varying periods, each of approximately one year in length. Precipitation records at each of these study area gages were extended to provide nine contemporaneous records. The extension of these precipitation records was accomplished by the following

weighting procedure based on the precipitation record at the Burns gage:

$$P_i' = \frac{P_i}{P_b} P_b' \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

in which

- $P_i'$  = estimated total precipitation at the  $i^{\text{th}}$  study area gage for the contemporaneous period
- $P_b'$  = observed total precipitation at Burns gage for the contemporaneous period
- $P_i$  = total precipitation at the  $i^{\text{th}}$  study area gage for the entire period of observed data at that gage
- $P_b$  = total precipitation at Burns gage for the same period as is used in calculating  $P_i$

To establish a criterion for obtaining the different precipitation amounts on each watershed, a multiple linear regression was performed for each data set. Mean annual precipitation was correlated with station elevation and east-west distance of the station from an arbitrary datum. The first data set provided the highest coefficient of correlation ( $R^2$ ) with a value of 0.89.

The regression equation (see Figures 7 and 8) is given as follows:

$$P = 40.127 - 0.995 (\text{Distance east of Steven's Pass}) + 0.007 (\text{Elevation}) \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

Equation 2 was used to estimate mean annual precipitation ( $P$ ) for a watershed based on its mean elevation and the distance east from Steven's Pass to the watershed's centroid of area. Daily precipitation for a watershed then was obtained by multiplying the corresponding daily precipitation measured at the Burns gage by the ratio of estimated mean annual precipitation for the watershed, to the mean annual precipitation at the Burns gage. It is emphasized that the regression equation used was obtained using data from stations located approximately 30 miles (48 km) from the study area.

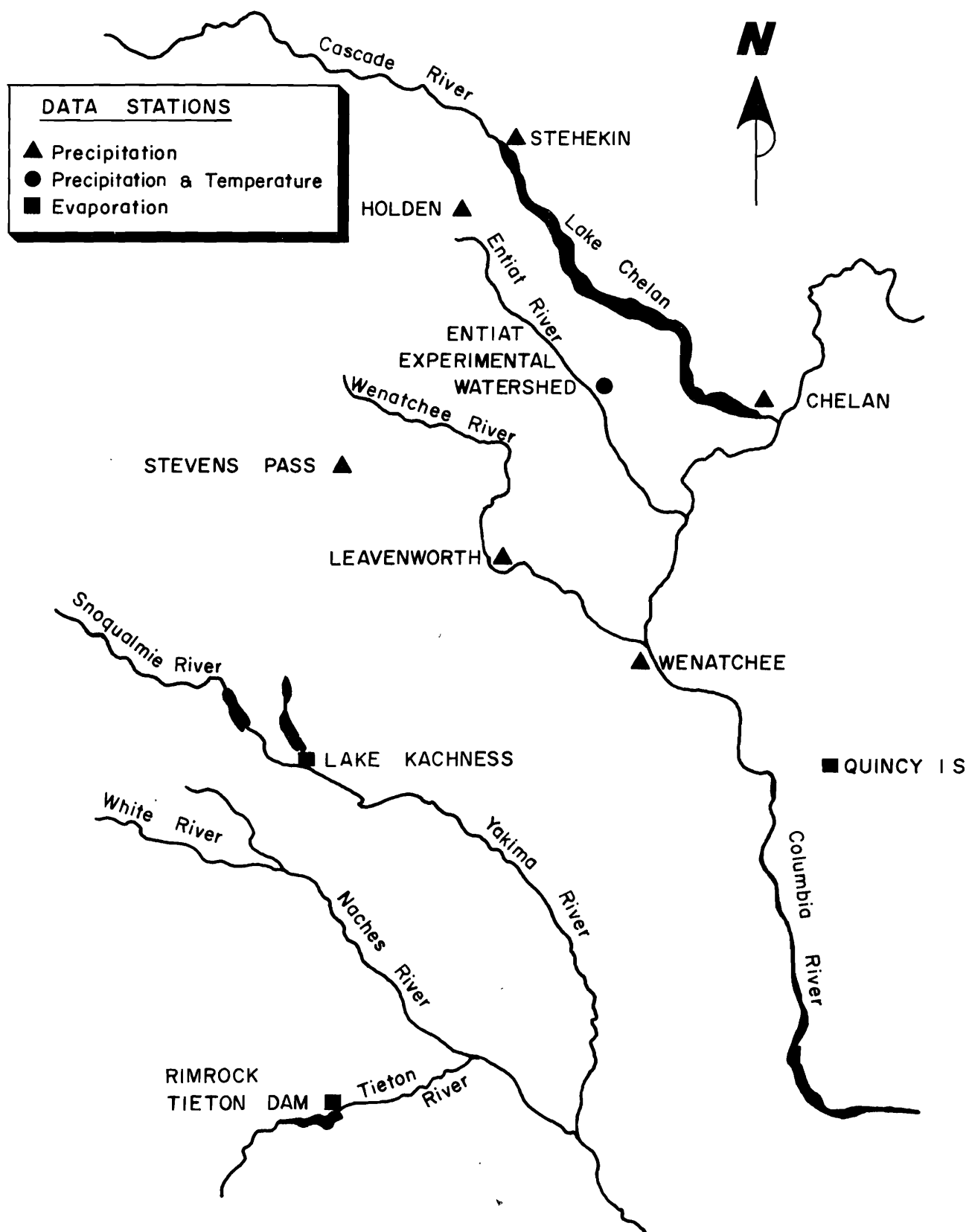


Figure 6. Map showing location of data stations.

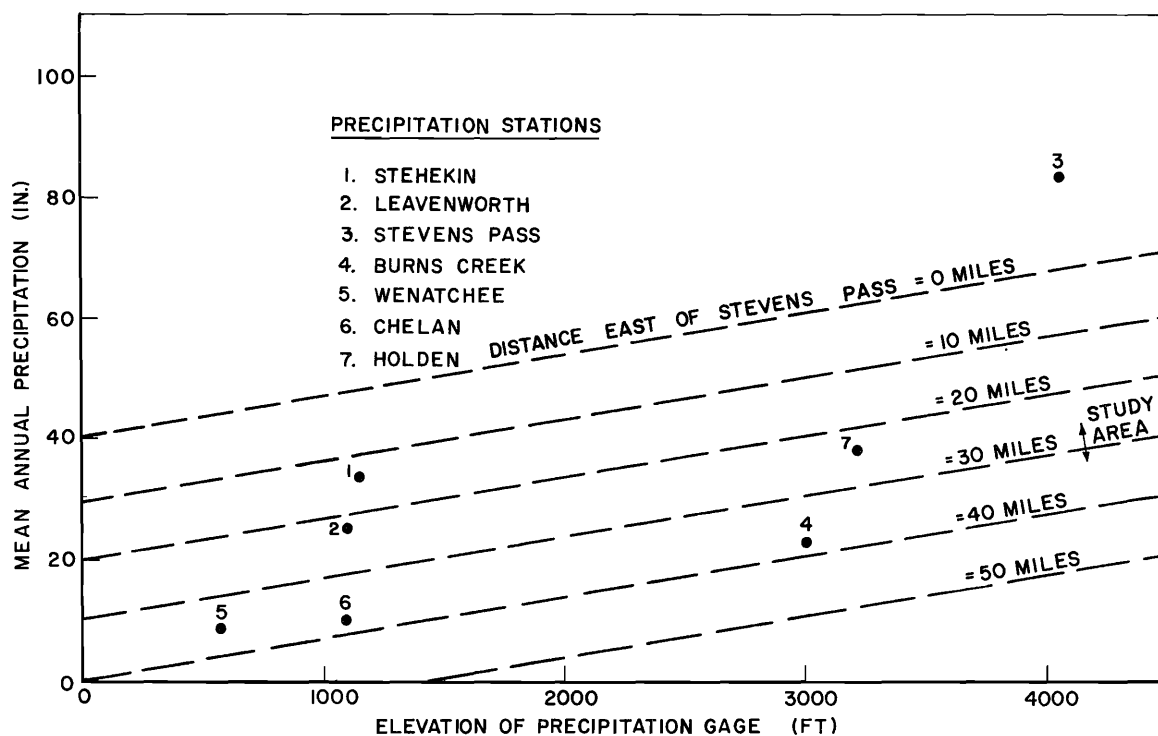


Figure 7. Mean annual precipitation versus precipitation gage elevation as a function of distance east of Steven's Pass for the set of precipitation stations approximately thirty miles from study area (1 in. = 25.4 mm, 1 ft. = 0.305 m, 1 mile = 1.61 km).

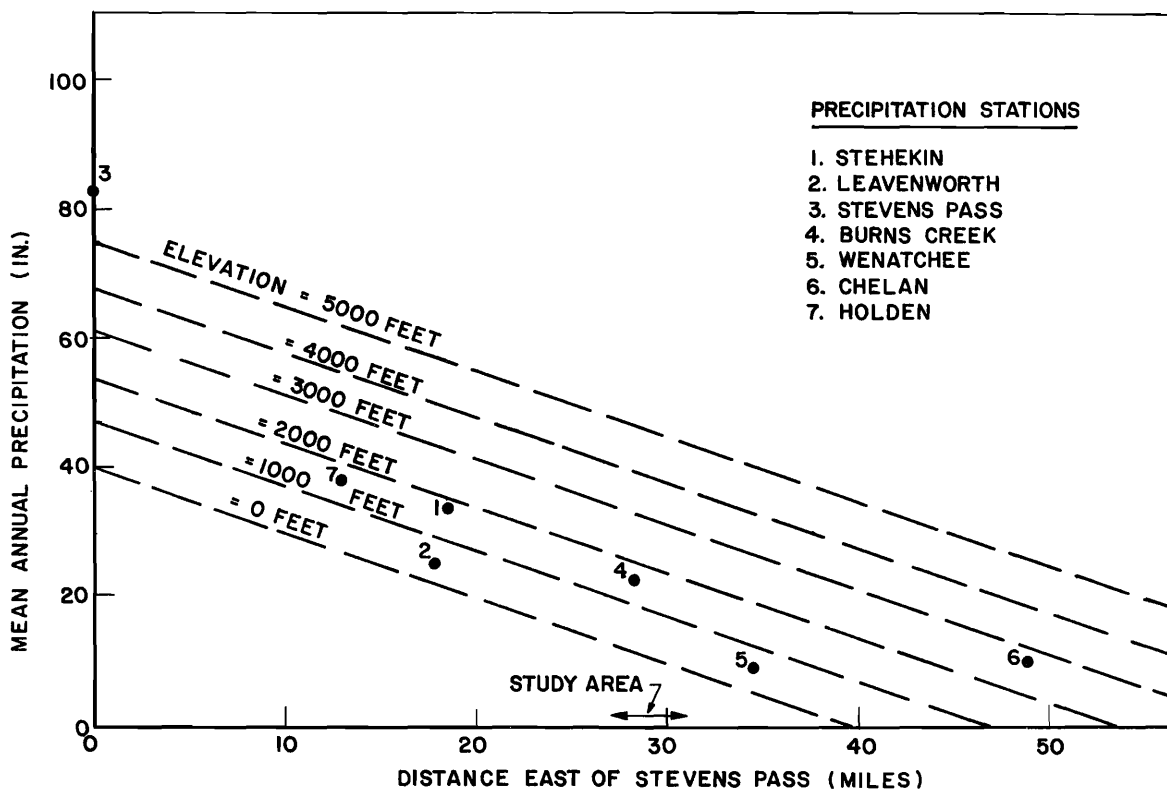


Figure 8. Mean annual precipitation versus distance east of Steven's Pass as a function of precipitation gage elevation for the set of precipitation stations approximately thirty miles from study area (1 in. = 25.4 mm, 1 ft. = 0.305 m, 1 mile = 1.61 km).

## Temperature

The daily temperature at the Burns station was lapsed to the mean elevation of each watershed. Monthly lapse rates were estimated by linear regression using lapse rates available for Spokane, Washington. The data were obtained from Climatological Data by the U.S. Department of Commerce (1961 through 1970).

## Evapotranspiration

Monthly pan evaporation and mean monthly temperature data were obtained from Climatological Data (1961 through 1970) for 10 years of record at Quincy 1S and Rimrock Tieton Dam. Records at Lake Kachness, an evaporation station closer to the study area than Rimrock Tieton Dam, were not available for the complete study period. Mean monthly amounts of evaporation, per °F of mean monthly temperature, were computed for both stations and the mean of these two values was used for the study area. This value was divided by the number of days in the month and multiplied by the temperature of a particular day to obtain an estimated potential evapotranspiration rate for that day. This approach for es-

timating potential evapotranspiration was adopted by Shih et al. (1972) in an earlier version of USUWSM.

## Solar radiation

At a particular location on the earth's surface the direction and degree of slope strongly influence the amount of direct solar radiation which is received on that slope. Thus, for a north-facing slope evapotranspiration and snowmelt rates tends to be lower than is the case for a south slope. For this reason, in the watershed hydrology model which is used an attempt is made to account for the average degree of slope and direction (aspect) of the area under study. The parameter which is applied is termed the solar radiation index (Lee, 1963; Riley et al., 1966). This index is a relative measure of the amount of direct solar radiation received by a given slope at a particular location and time to that received by a horizontal surface at the same location and time. Because the effects of atmospheric conditions are assumed to be the same for both surfaces in the same location, atmospheric effects are assumed to be removed. Monthly radiation index values for each watershed were determined as a function of aspect, percent slope, and time of year. Because the average slope, aspect, and latitude are essentially the same for each of the three watersheds, the same monthly radiation index value was applied to each area. These values are shown by Table 1 which appears later in the report in Chapter V.

## CHAPTER IV

### THE UTAH STATE UNIVERSITY WATERSHED SIMULATION MODEL

The basic model used in this project is termed the Utah State University Watershed Simulation Model (USUWSM), and was first developed by Riley et al. (1966). Shih (1971) extended this work in a study of water budgeting and weather modification for the Weber River Basin, Utah. The model was further modified by Shih et al. (1972) and was successfully applied to a watershed in the H.J. Andrews Experimental Forest for the Coniferous Forest Biome (Chambers, 1973). In addition, the model was applied to the Olympus Cove area, Salt Lake County, Utah (Riley et al., 1974) in a hydrologic study of an urbanizing watershed. The model is currently being used in a bio-hydrologic study of Spawn Creek, near Logan, Utah (Twedt, 1975).

USUWSM is a lumped parameter model with a time increment of one day. Some changes and refinements were made to the model during the study to account for characteristics of the prototype relating to the unresponsiveness of streamflow to rainfall and the importance of snow. Figure 9 is a simplified flow chart of the hydrologic system represented by the model. A listing of the FORTRAN computer program is contained in the Appendix. Brief descriptions of each component of the model are given by the following paragraphs.

#### Interception

Interception is that part of precipitation which is temporarily held by forest canopies and then returned to the atmosphere by evapotranspiration or sublimation. The amount of interception depends on storm size and intensity, and canopy type and density. For each storm the available interception storage capacity of the canopy must be satisfied before precipitation is assumed to reach the ground surface. Hence the potential amount of interception abstraction at any time is given by  $S_i - S_i(t)$  where  $S_i$  is the maximum interception storage capacity of the canopy and  $S_i(t)$  is the interception storage occupied at time  $t$ . For the study areas, the average value of  $S_i$  was determined through the calibration procedure to be 0.2 inches (5 mm). Because evaporation had depleted previous interception storage quantities, for most storms the initial value of  $S_i(t)$  was zero.

#### Snow accumulation and ablation

Figure 10 is a flow chart of the snow accumulation and ablation processes. The following temperature criterion is used to divide the daily precipitation (P) into rain (R) and snow (S) (Figure 11):

$$SN = P \frac{T_r - T_a}{T_r - T_s}, \quad T_s < T_a < T_r \quad (3a)$$

$$SN = 0, \quad T_a \geq T_r \quad (3b)$$

$$SN = P, \quad T_a \leq T_s \quad (3c)$$

$$R = P - SN, \quad \text{for all } T_a \quad (3d)$$

in which  $T_a$  is the mean daily temperature;  $T_r$  is the temperature above which all precipitation is treated as rain; and  $T_s$  is the temperature below which all precipitation is treated as snow. The above relationship is drawn from earlier work by the U.S. Army Corps of Engineers (1956). The values determined during the calibration process for  $T_r$  and  $T_s$  were 38°F (3.3°C) and 30°F (-1.1°C) respectively.

Snowmelt rate depends primarily upon the rate of energy input to the snowpack. However, the complex nature of the process and the scarcity of relevant data prevent a strictly analytical approach to the simulation of snowmelt. Air temperatures are frequently used as an index of available energy (Pysklywec et al., 1968; Anderson and Crawford, 1964; Amorocho and Espildora, 1966; and Eggleston et al., 1971).

A degree day approach shown in Equation 4 and based on the work of Eggleston et al. (1971) was used to represent the snowmelt process at the surface of the snowpack. Equation 4 consists of two terms, a radiation melt term and a rain on snowmelt term.

$$M_{sr} = \overbrace{k_m R I (T_e - T_m)(1 - A)}^{\text{radiation}} + \overbrace{(T_a - 32) \frac{R}{144}}^{\text{rain on snow}} \quad (4)$$



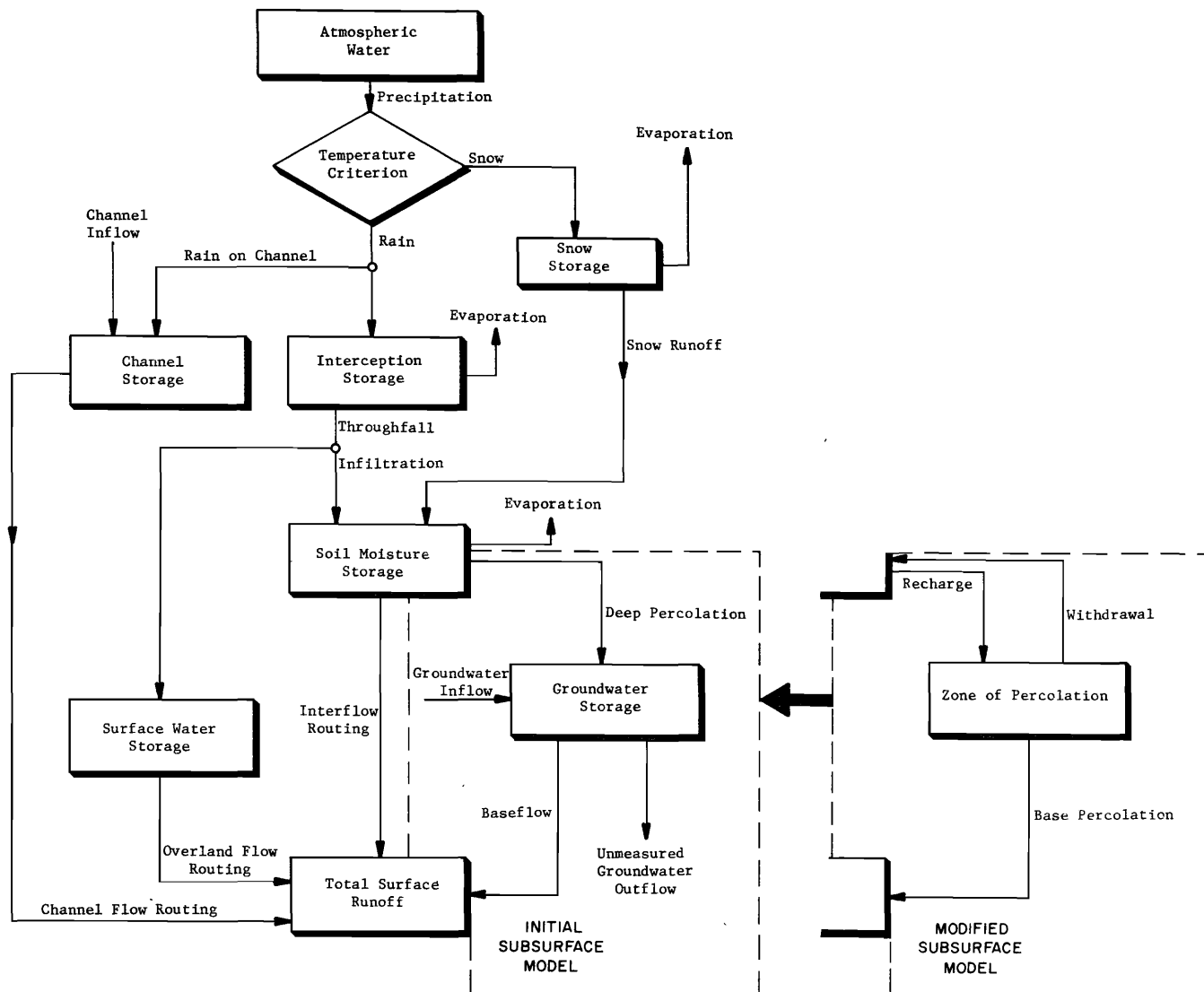


Figure 9. Simplified flow chart of the hydrologic system represented by USUWSM.

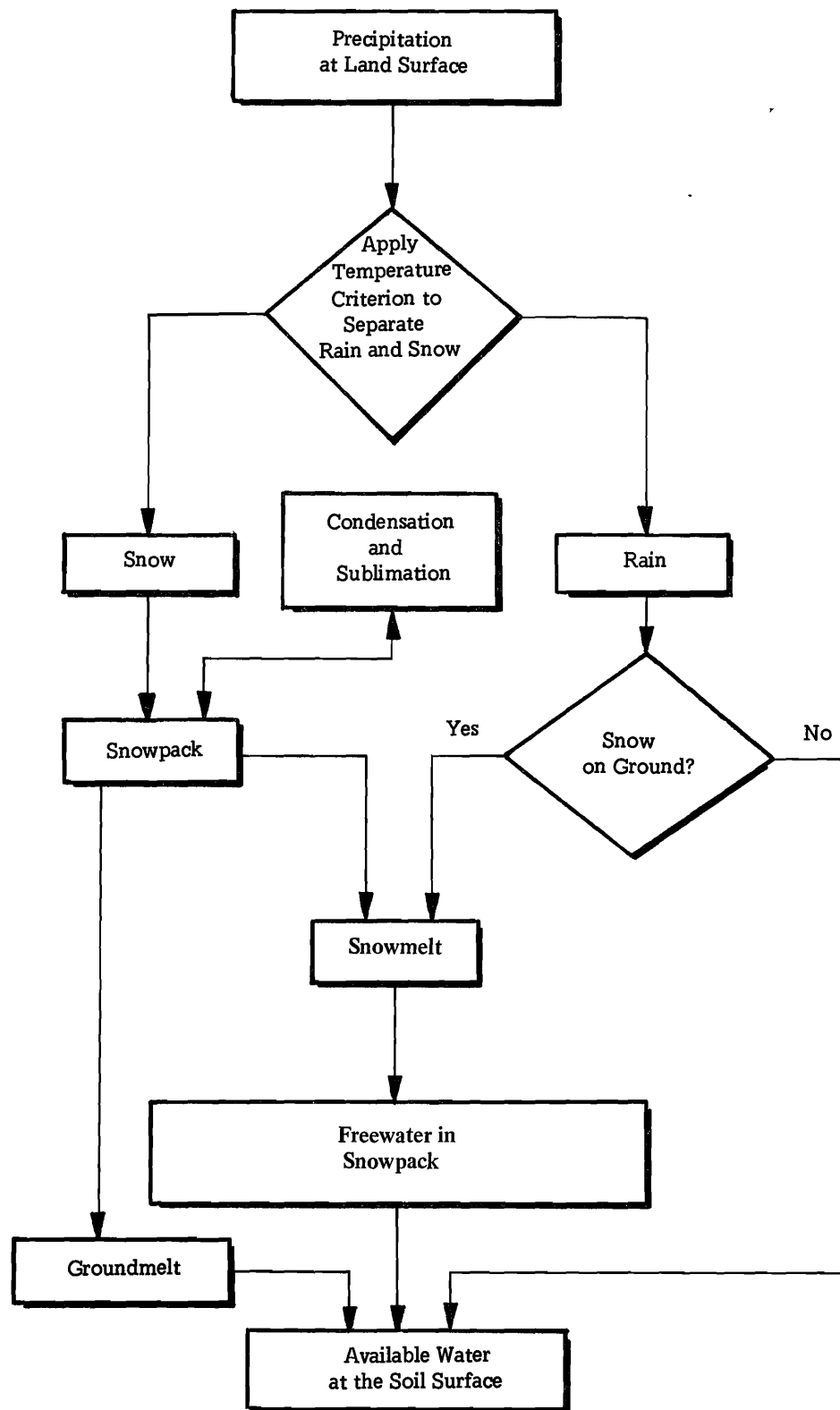


Figure 10. Flow chart of the snow accumulation and ablation processes represented by USUWSM.

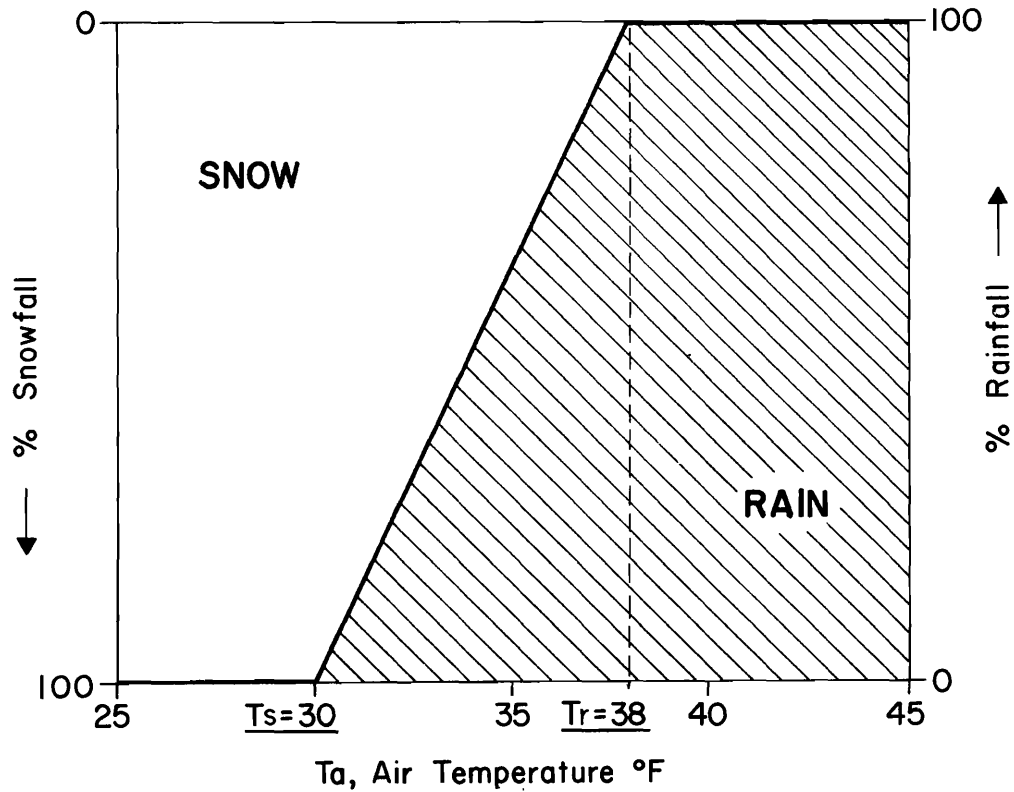


Figure 11. Temperature criterion used to divide daily precipitation into rain and snow ( $^{\circ}\text{F} = 9/5 ^{\circ}\text{C} + 32$ ).

in which  $M_{rs}$  is the daily snowmelt amount in inches;  $k_m$  is the snowmelt coefficient;  $RI$  is the monthly radiation index for the study area;  $T_a$  is the mean daily air temperature in  $^{\circ}\text{F}$ ;  $T_e$  is the snowpack temperature in  $^{\circ}\text{F}$ ;  $T_m$  is the temperature at which snowmelt commences in  $^{\circ}\text{F}$ ;  $R$  is the rainfall in inches, and  $A$  is the albedo or reflectivity of the snowpack surface.

Albedo is calculated in the following manner:

$$A = 0.4 (1 + e^{-0.2 \text{SDAY}}), R = 0 \quad . \quad (5a)$$

$$A = 0.4, R > 0 \quad . \quad (5b)$$

in which  $\text{SDAY}$  is the number of days since the last snowfall. Thus, albedo decreases during periods without fresh snow and reaches a lower limit of 0.4 when rainfall occurs.

Freewater in the snowpack comprises snowmelt and rain that has fallen onto the snowpack (see Figure 10). The freewater either freezes within the snowpack or emerges from the bottom of the pack after its

liquid water holding capacity is satisfied and enters the soil moisture zone. There also exists a possibility of evaporation of freewater which is considered later in the description of the evaporation component of the model. In the study area the large change in elevation and consequent change in air temperatures results in a variation of snowmelt and therefore depth of freewater over the watershed. Runoff from the snowpack will occur when the depth of freewater ( $F$ ) exceeds the liquid water holding capacity ( $\text{WHC}$ ) of the snowpack. In the prototype system the situation of freewater depths exceeding the water holding capacity occurs earlier in the snowmelt season at lower elevations than at higher elevations. Thus, snow runoff takes place at lower elevations before higher elevations. However, the lumped parameter model simulates snow runoff over the entire watershed area when the depth of freewater at the mean elevation exceeds the water holding capacity of the snowpack.

The dependency of the lumped parameter model on the freewater status at only the mean elevation results in a significant discrepancy in the timing of snow runoff for the study area in which large elevation

changes are present. For example, on some days actual snow runoff will occur from lower elevations before it occurs at the mean elevation. On these days simulated runoff was zero because  $F < WHC$  at the mean elevation and therefore the actual snow runoff from the lower elevations was not simulated. Another example is the situation in which actual snow runoff occurs at the mean elevation but not at higher elevations. Under these conditions the simulated snow runoff volume was equal to the depth of snow runoff ( $F - WHC$ ) multiplied by the entire watershed area including the higher elevations where no snow runoff actually occurred.

To improve the timing of snow runoff it was necessary to introduce a method of accounting for the variation in  $F$ , the freewater depth over the different elevation ranges in the watershed area. The distributed parameter approach in which each watershed is divided into several spatial units based on elevation intervals was ruled out by the lack of sufficient data. A procedure was devised in which spatial resolution of the lumped parameter model was improved without resorting to reduced spatial units. It was assumed that there existed a linear variation in freewater depth ( $F'$ ) over the watershed area. Figure 12 shows three cases that may arise:

Case I: Freewater depth ( $F'$ ) over part of the watershed is less than WHC and over the remainder of the watershed is above WHC. In this case, only that part of the watershed area in which  $F' > WHC$  contributes to snow runoff. The amount of snow runoff is found by calculating the cross-hatched area between  $F'$  and WHC when  $F' > WHC$ . By simple geometry it can be shown that the volume of snow runoff is:

$$SNRF = \frac{(F + S/2 - WHC)^2}{2S} \quad \dots (6)$$

Case II: Freewater depth ( $F'$ ) is greater than WHC over the entire watershed. Snow runoff takes place over the total watershed area. The volume of snow runoff is:

$$SNRF = F - WHC \quad \dots (7)$$

Case III: Freewater depth ( $F'$ ) is less than WHC over the entire watershed and therefore no snow runoff occurs:

$$SNRF = 0 \quad \dots (8)$$

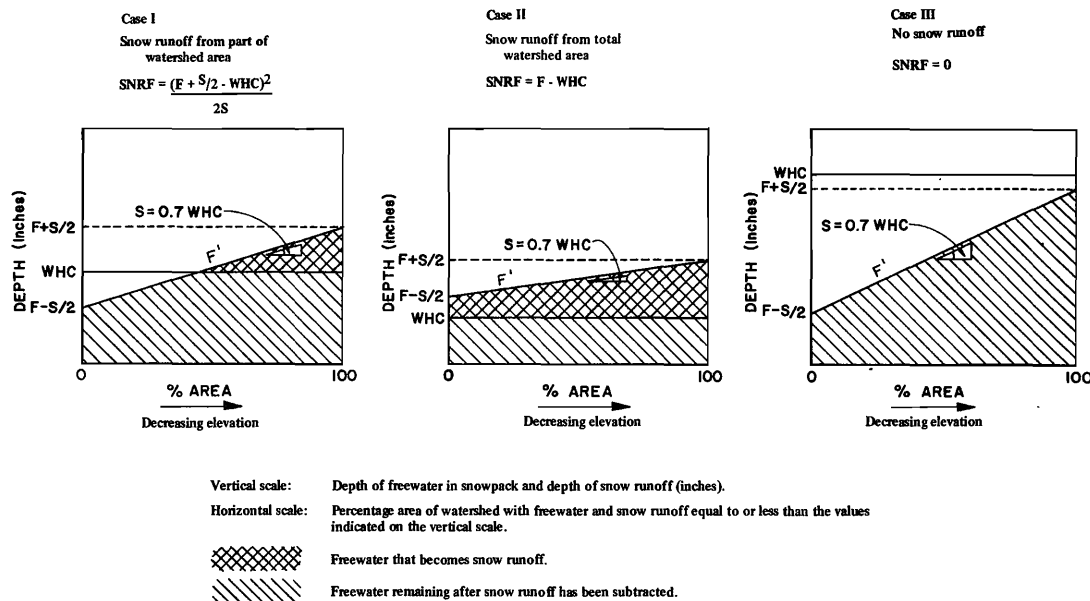


Figure 12. Three cases illustrating the method of estimating snow runoff (1 in. = 25.4 mm).

The cross-hatched areas of Figure 12 represent the volume of snowmelt runoff, while the shaded areas represent the volume of freewater remaining after snow runoff, has been subtracted. Vertical axes represent depths of freewater and snow runoff and horizontal axes represent percent watershed area. The choice of percent watershed area for the horizontal axes results in the snow runoff volume SNRF being expressed as an equivalent depth in inches over the entire watershed area. In this way, SNRF is compatible with the other variables in the model which also are stored as depths in inches.

Previous versions of the snow model did not include any consideration of variation in snow runoff at different locations in the watershed and were therefore equivalent to a situation in which  $S = 0$ . In cases II and III SNRF is independent of  $S$ , and thus it is only in Case I that the modified version of the snow model yields a different value of SNRF when compared with the original model.

From model verification procedures, depth of freewater and percentage area of the watershed were found to be related by a factor of  $S = 0.7$  (WHC); where WHC, the water holding capacity of the snowpack, was found to be five percent of the snowpack depth. Model calibration indicated that groundmelt from snowpack takes place at the rate of SNGM = 0.01 inches per day (0.3 mm per day). This quantity of groundmelt was added directly to soil moisture storage.

### Channel precipitation

During a storm, part of the precipitation falls close to, or into the stream channel, without being subject to the delaying effects of infiltration and subsurface flow. On the basis of the proportion of total watershed area adjacent to a stream channel, one percent of rainfall was treated as channel precipitation. Surface runoff and channel precipitation are treated as linear reservoirs with a common decay constant,  $k_s$ . The linear reservoir is based on the assumption that the rate of discharge from a storage reservoir is proportional to the quantity of water in storage (Figure 13), that is:

$$q = \frac{dS(t)}{dt} = -k_s S(t) \quad (9)$$

in which

- $q$  = is the discharge rate from the reservoir
  - $S(t)$  = is the storage within the basin at any time,  $t$
  - $k_s$  = is a decay constant for surface runoff and channel precipitation depending upon the basin characteristics (channel precipitation)
- The value of  $k_s$  was established as unity by model verification studies.

### Soil moisture

The model allows water entering the root zone to satisfy the retention capacity ( $M_{cs}$ ) of the soil before interflow and percolation can commence. Only that part of soil moisture which is subject to yearly change is modeled. Thus, soil moisture storage is computed by considering the amount of water removed from the soil profile by interflow, deep percolation, and evapotranspiration and the amount of water added by infiltration and groundmelt from snowpack.

### Infiltration

Surface organic conditions, physical characteristics of the soil, and soil moisture conditions influence the capacity rate of infiltration into the root zone at any time,  $t$ , ( $f_r$ ) of water available at the ground surface. Before surface runoff can occur the rate of water supply to the ground surface by rainfall or snowmelt must exceed the capacity infiltration rate. Helvey (1973) reported that no surface runoff was observed before the 1970 fire. When  $M_s(t)$ , the soil moisture storage at time  $t$  is less than saturation capacity ( $M_{ss}$ ), additional infiltration capacity above the equilibrium rate ( $f_c$ ) was represented as being proportional to the difference between  $M_s(t)$  and  $M_{ss}$ . Thus, the capacity infiltration rate ( $f_r$ ) is computed as follows:

$$f_r = f_c + f_o \frac{(M_{ss} - M_s(t))}{M_{ss}} \quad (10)$$

in which  $f_c$  is the equilibrium infiltration rate and  $f_o$  is the incremental infiltration rate in excess of  $f_c$ . The infiltration of water to the soil reduces the soil moisture deficit ( $M_{ss} - M_s(t)$ ), and thus the infiltration rate also is decreased, as indicated by Equation 10 (see Figure 14).

### Evapotranspiration

Factors affecting evapotranspiration (ET) include temperature, solar radiation, wind, humidity, and the current soil moisture status. Many techniques of estimating ET are available in the literature. The selection of a particular method usually is restricted by the ability to meet the data requirements of the method.

In the approach adopted for this study, potential evapotranspiration (PET) is computed using the following expression:

$$PET = T_a \frac{CP(m)}{D(m)} \quad (11)$$

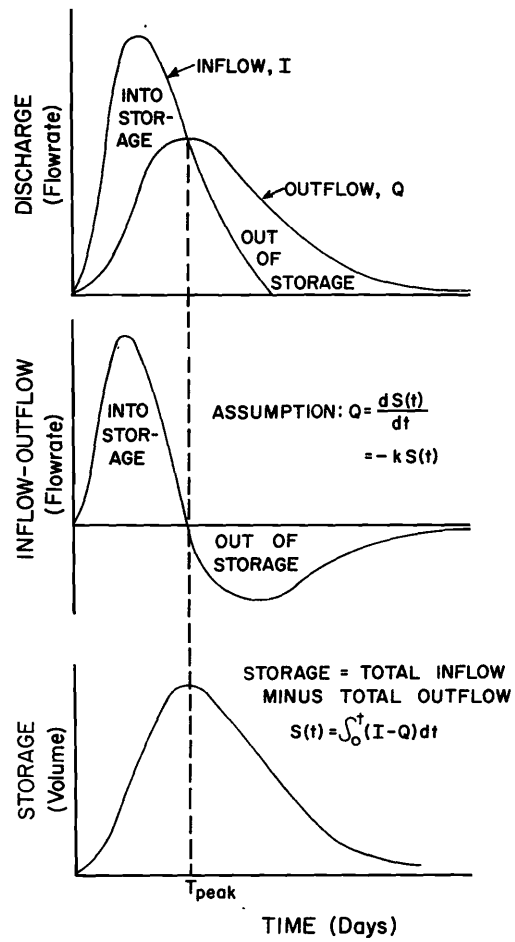


Figure 13. Linear reservoir.

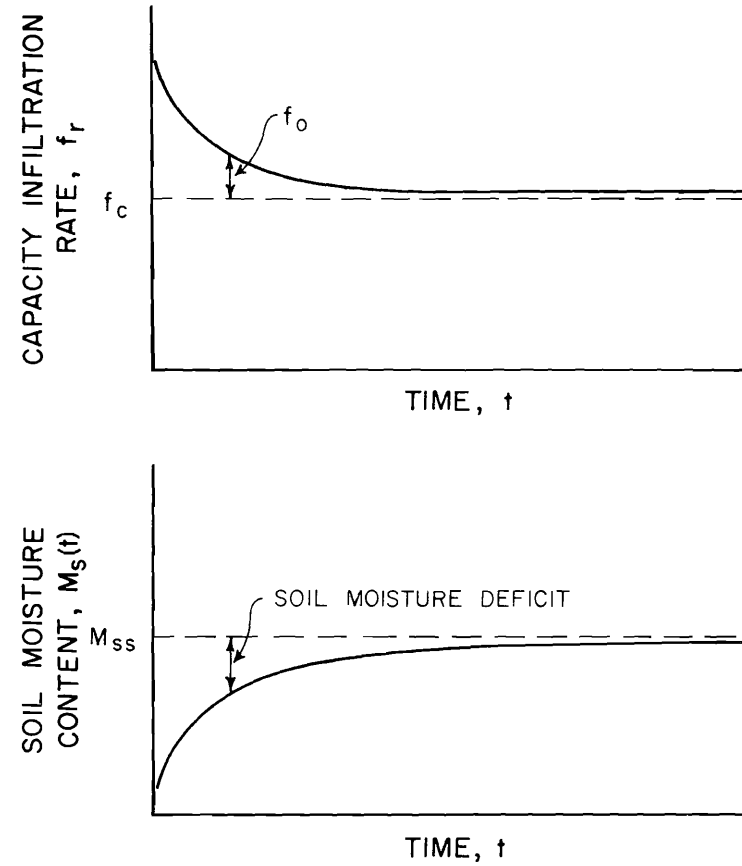


Figure 14. Relationship between reduction in infiltration rate and reduction in soil moisture deficit during a storm of several days duration.

in which  $T_a$  is the mean daily air temperature in  $^{\circ}\text{F}$ ;  $\text{CP}(m)$  is the evapotranspiration per  $^{\circ}\text{F}$  of mean monthly temperature for the  $m^{\text{th}}$  month; and  $D(m)$  is the number of days in the  $m^{\text{th}}$  month. PET is satisfied by the following storages in the order in which they are listed: interception storage, snowpack, and soil moisture storage. Thus, if PET exceeds interception storage but is less than the sum of interception and snow storages, then interception storage is depleted, snow storage is reduced by the difference between PET and interception storage, and the ET will equal PET.

In the case where evapotranspiration is taken from soil moisture, ET will equal PET provided soil moisture is above a critical point ( $M_{es}$ ). This point was found to be two inches (51 mm) through the calibration process. When soil moisture storage ( $M_s(t)$ ) is below  $M_{es}$ , that portion of PET which is unsatisfied by interception and snow storages is reduced by the ratio of  $M_s(t)$  to  $M_{es}$  according to a technique first proposed by Riley and Chadwick (1967).

The following equations cover each possible case of determining ET from PET based on the status of the interception storage ( $S_i(t)$ ), the snowpack ( $M_{sn}(t)$ ), and the soil moisture storage ( $M_s(t)$ ):

I If  $\text{PET} \leq S_i(t)$

$$\text{ET} = \text{PET} \quad (12a)$$

$$S_i(t+1) = S_i(t) - \text{PET} \quad (12b)$$

$$M_{sn}(t+1) = M_{sn}(t) \quad (12c)$$

$$M_s(t+1) = M_s(t) \quad (12d)$$

II If  $S_i(t) < \text{PET} \leq S_i(t) + M_{sn}(t)$

$$\text{ET} = \text{PET} \quad (13a)$$

$$S_i(t+1) = 0 \quad (13b)$$

$$M_{sn}(t+1) = M_{sn}(t) - (\text{PET} - S_i(t)) \quad (13c)$$

$$M_s(t+1) = M_s(t) \quad (13d)$$

III If  $S_i(t) + M_{sn}(t) < \text{PET} \leq S_i(t) + M_{sn}(t) + (M_s(t) - M_{es})$

$$\text{ET} = \text{PET} \quad (14a)$$

$$S_i(t+1) = 0 \quad (14b)$$

$$M_{sn}(t+1) = 0 \quad (14c)$$

$$M_s(t+1) = M_s(t) - (\text{PET} - S_i(t) - M_{sn}(t)) \quad (14d)$$

IV If  $S_i(t) + M_{sn}(t) + (M_s(t) - M_{es}) < \text{PET}$  and if

(i)  $M_s(t) > M_{es}$

$$\text{ET} = S_i(t) + M_{sn}(t) + M_s(t) \quad (15a)$$

$$S_i(t+1) = 0 \quad (15b)$$

$$M_{sn}(t+1) = 0 \quad (15c)$$

$$M_s(t+1) = M_{es} \quad (15d)$$

(ii)  $M_s(t) \leq M_{es}$

$$\text{ET} = S_i(t) + M_{sn}(t) + \frac{M_s(t)}{M_{es}} (\text{PET} - S_i(t) - M_{sn}(t)) \quad (16a)$$

$$S_i(t+1) = 0 \quad (16b)$$

$$M_{sn}(t+1) = 0 \quad (16c)$$

$$M_s(t+1) = M_s(t) - \frac{M_s(t)}{M_{es}} (\text{PET} - S_i(t) - M_{sn}(t)) \quad (16d)$$

### Interflow

Interflow ( $N_r$ ) moves laterally within the root zone and reaches a surface channel more quickly than groundwater but less quickly than overland flow. Percolation and interflow,  $G_s$ , occur when the soil moisture content ( $M_s$ ) exceeds the holding capacity of the soil  $M_{cs}$ .

Thus:

$$G_s = M_s(t) - M_{cs}, M_s(t) > M_{cs} \quad (17a)$$

$$G_s = 0, M_s(t) \leq M_{cs} \quad (17b)$$

The combined rate of percolation and interflow,  $G_d$ , is estimated by a linear reservoir equation which contains a decay constant,  $k_g$ . Thus:

$$G_d = (1 - e^{-k_g}) G_s \quad (18)$$

In the model interflow rate is computed as follows:

$$N_r = G_d - G_r, G_s > 0 \quad (19a)$$

$$N_r = 0, G_s \leq 0 \quad (19b)$$

in which the rate of percolation ( $G_r$ ) is given by Equation 23 below.

### Baseflow

In the original version of USUWSM baseflow was represented as the outflow from groundwater storage treated as a linear reservoir:

$$\text{BF}(t) = -k_b G(t) \quad (20)$$

in which

$\text{BF}(t)$  = baseflow at time,  $t$

$k_b$  = linear reservoir decay constant for groundwater storage  
 $G(t)$  = groundwater storage at time  $t$

However, this model resulted in a poor match between predicted and observed streamflow during the period of low flows occurring between successive snowmelt seasons (Bowles and Riley, 1975). For this period of almost uniform observed flows, predicted streamflow decreased in an approximately exponential fashion. This trend in the computed results was attributed to the low rate at which deep percolation in the model replenishes the groundwater body. The situation can be approximated by a linear reservoir with outflow but no inflow. It can be shown that the outflow, in this case baseflow, decreases in an exponential manner described by:

$$BF(t) = BF(0) \exp(-k_b t) \quad (21)$$

Substituting Equation 20 into Equation 21 yields

$$BF(t) = -k_b G(0) \exp(-k_b t) \quad (22)$$

On the basis of Equation 22 initial groundwater storage  $G(0)$  was made large and  $k_b$  was assigned a small value. As a result, the magnitude of predicted baseflow,  $BF(t)$ , remained fairly steady during the low flow period. However, the snowmelt hydrograph was poorly reproduced due to the excessive dampening of responses from the groundwater reservoir. In addition, the values of initial groundwater storage,  $G(0)$ , were unrealistically large for the small and steep Entiat watersheds.

The linear reservoir assumption that the rate of baseflow from the groundwater body is proportional to the quantity of water in groundwater storage appeared to be unsuited to the steep Entiat watersheds. While the linear groundwater reservoir functioned well for snowmelt periods, it lacked the capability to reproduce low flows. Therefore, a different approach to the subsurface part of the hydrology simulation model was sought.

The modified view of the streamflow generation process of the steep Entiat watersheds is illustrated in Figures 9 and 15. Baseflow from the saturated groundwater zone was replaced by a quantity termed base percolation. This quantity is sustained by flow from a zone of percolation between the root zone and underlying

bedrock. When water infiltrating through the soil surface is insufficient to maintain soil moisture close to its retention capacity, water is withdrawn from the zone of percolation and added to the root zone. Physically this process is explained by capillary conduction under the influence of plant roots. When soil moisture storage exceeds its retention capacity water leaves the root zone by free drainage as interflow and recharge to the underlying zone of percolation. Thus, the effects of capillary movement from the zone of percolation, recharge to the zone of percolation, and, to a lesser extent, interflow are that they tend to maintain the soil moisture storage of the root zone at its retention capacity. These effects are demonstrated by Figure 16, which indicates that soil moisture was supplemented by withdrawals from the zone of percolation during the months of July through October when evapotranspiration was high. Recharge took place during the period of snowmelt and to a lesser extent throughout the entire snow accumulation period.

The rate of interflow is given by Equation 19, and the rate of recharge by percolation,  $G_r$ , as follows:

$$G_r = (1 - k''_d) G_d = RH \quad (23)$$

in which

$k''_d$  = proportion of  $G_d$  that becomes interflow

The proportion of  $G_d$  that becomes interflow is adjusted to become smaller as the magnitude of the soil moisture surplus ( $M_s(t) - M_{cs}$ ) increases, although the actual amount of interflow continues to increase (Figure 17). This effect is achieved by varying  $k''_d$  according to the following equation:

$$k''_d = k'_d \left\{ 1 - \frac{[M_s(t) - M_{cs}]}{M_{ss}} \right\} \quad (24)$$

in which

$k'_d$  = value of  $k''_d$  approached as  $M_s(t)$  approaches  $M_{cs}$  from above; dependent on slope and relative magnitudes of vertical and horizontal permeability  
 $M_{ss}$  = saturated soil moisture storage

The rate at which soil moisture is replenished by withdrawal (WD) of water from the zone of percolation is



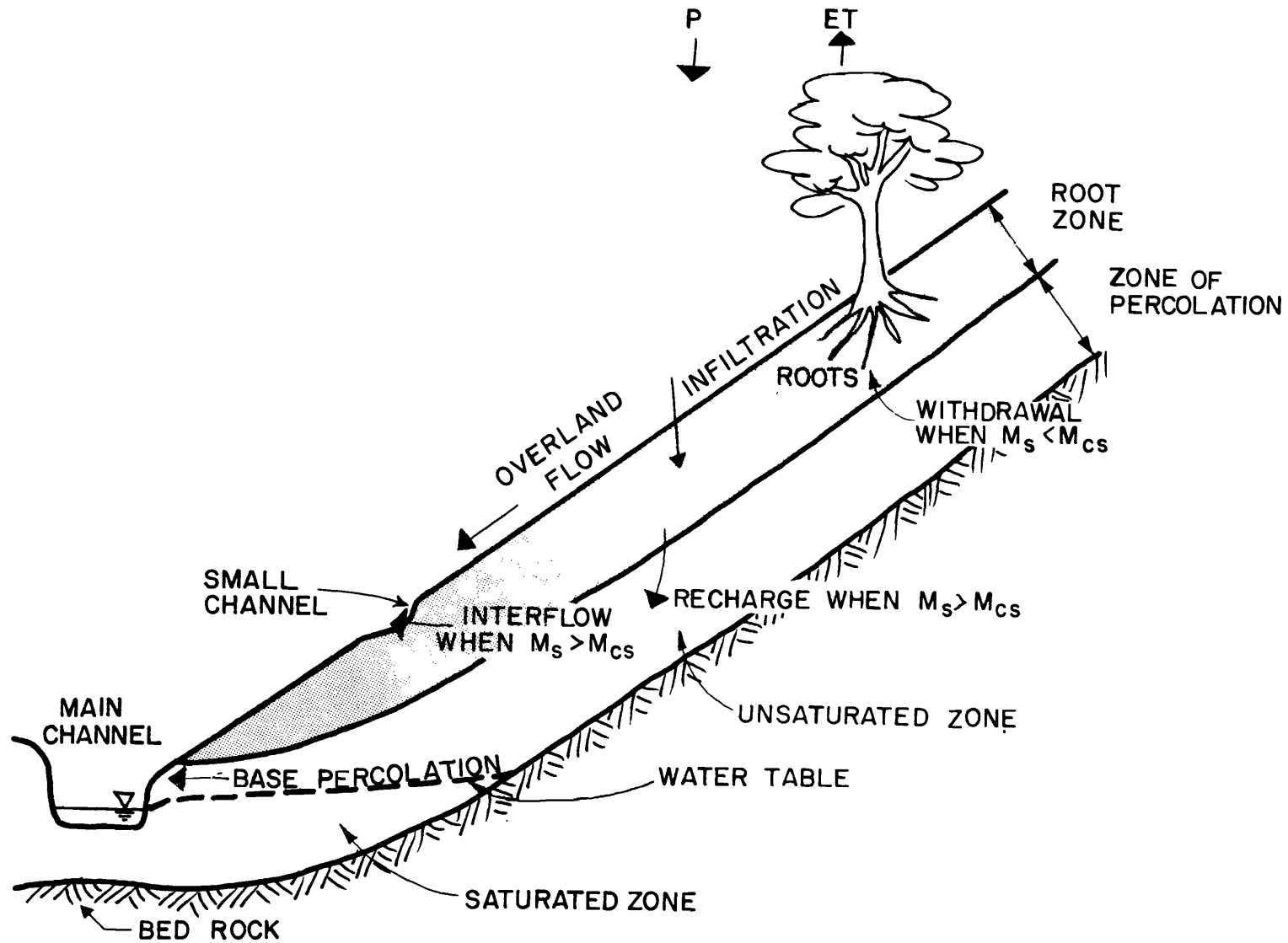


Figure 15. The terrestrial part of the hydrologic cycle in a steep mountain watershed as represented by modified USUWSM

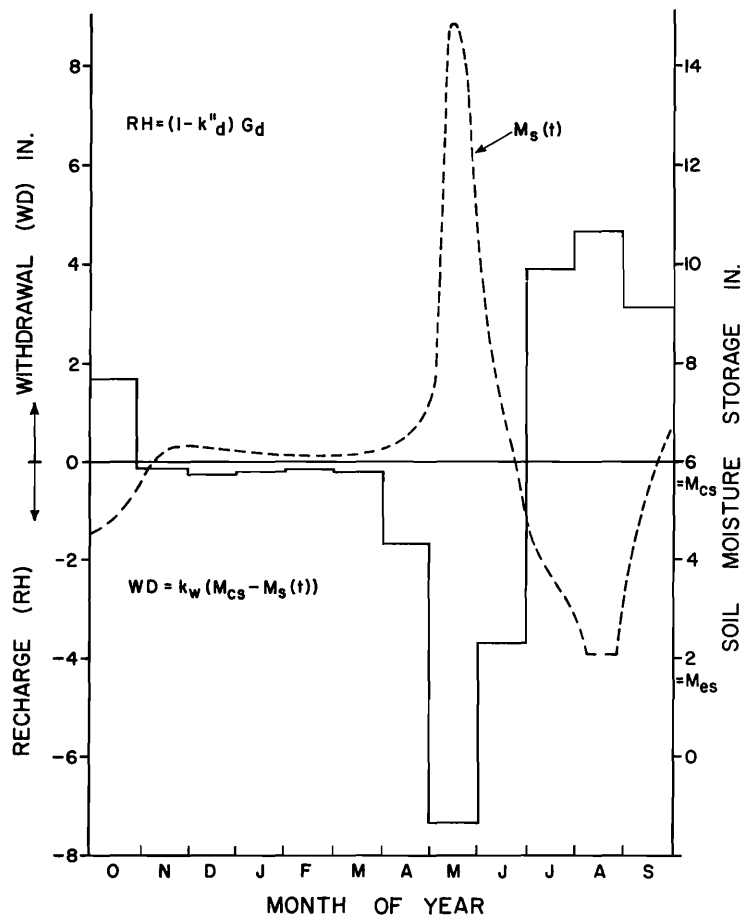


Figure 16. Recharge, withdrawal, and soil moisture storage on McCree Creek, for water year 1964. (1 in. = 25.4 mm).

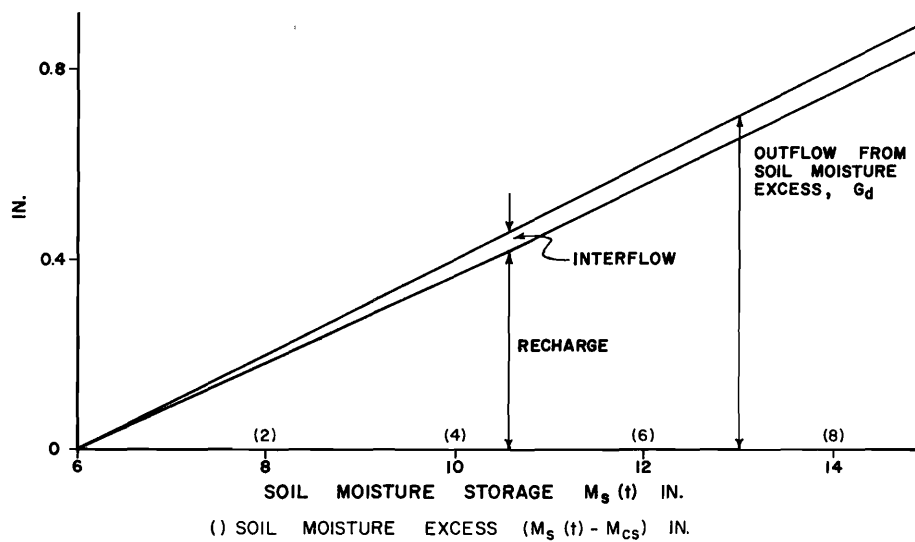


Figure 17. Variation of proportion of outflow from soil moisture excess that becomes interflow and recharge (1 in. = 25.4 mm).

assumed to take place in proportion to the magnitude of the soil moisture deficit:

$$WD = k_w [M_{cs} - M_s(t)], M_s(t) < M_{cs} \quad (25a)$$

$$WD = 0, M_s(t) \geq M_{cs} \quad (25b)$$

in which

$$k_w = \text{proportion of soil moisture deficit made up by withdrawal}$$

To summarize the conditions for interflow, recharge, and withdrawal, if  $M_s(t) < M_{cs}$  then interflow and recharge rates are zero, and the rate of withdrawal from the zone of percolation is given by Equation 25a. If  $M_s(t) > M_{cs}$ , the withdrawal rate is zero, and the interflow and recharge rates are given by Equation 19a and 23 respectively, with  $k''_d$  being given by Equation 24.

Baseflow percolation from the zone of percolation was assumed to be dependent on the history of the total quantity of water stored within that zone. Graupe, Isailovic, and Yevjevich (1975) used a moving average approach to represent the delayed response of a Karst aquifer. A similar approach was adopted in the modified model. Given the present value of a function,  $F(t)$ , and the  $(n-1)$  most recent previous values of that function, the moving average is obtained as follows:

$$\text{Moving average} = \frac{1}{n} \sum_{\tau=t-n+1}^{\tau=t} F(\tau) \quad (26)$$

Because the magnitude of storage in the zone of percolation was not readily obtainable, the variation of the percolation zone storage was approximated by the variation in soil moisture storage. The justification for the approach was that higher levels of soil moisture storage result in low withdrawals from the zone of percolation, and thus a greater magnitude of storage in that zone. Thus, base percolation was modeled as being proportional to an approximate moving average of soil moisture storage values:

$$SMMA(t) = \frac{(n-1) SMMA(t-1) + M_s(t)}{n} \quad (27)$$

and

$$BP = -k_g SMMA(t) \quad (28)$$

in which

$$SMMA(t) = \text{approximate moving average of soil moisture storage at time } t$$

$n$  = number of days on which approximate moving average is based (found to be 90 days by calibration procedure)  
 $k_g$  = proportion of SMMA(t) that becomes base percolation

The amount of storage in the zone of percolation was not accounted for in the modified model. Only the inflow from soil moisture and outflows to soil moisture and as baseflow were modeled. Therefore, the internal mass balance of the model was lost. However, over an eight year period the simulation results indicated that in the long run inflow to the zone of percolation was approximately equal to outflow. If outflow to soil moisture and as baseflow was consistently greater than inflow from soil moisture this may indicate that water from outside the watershed was entering the zone of percolation.

Initial attempts to model the Entiat watersheds were based on the generally accepted explanation of non-snowmelt streamflow (baseflow) which assumes that extensive, saturated groundwater aquifers feed streams during nonstorm periods. Storm or snowmelt streamflows were assumed to come from overland or subsurface flow through interconnecting channels below the soil surface (interflow).

The difficulty with assuming a linear groundwater reservoir was that, with reasonable values of groundwater storage  $G(0)$  for the size of watershed, the predicted streamflow dropped below observed values. This shortcoming was due to the slow rate of replenishment of groundwater storage by deep percolation attributed to extended periods of severe soil moisture deficit. Thus, when soil moisture storage was supplemented by withdrawal from the zone of percolation streamflow predictions were improved.

In an experimental study in deep-soiled areas of the southern Appalachians, Hewlett and Hibbert (1963) "concluded that unsaturated flow in the earth mantle of steep watersheds cannot be ignored in hydrograph analysis, since it may well be a primary mechanism for sustaining baseflow. Groundwater wells at the experimental site failed to show significant saturated aquifers except along streams and drainageways, where accumulated water appears as spring or seepage flow. Because of the steep topography, these areas occur only in the immediate vicinity of the stream, a zone which appears too small to sustain streamflow through the summer period of high evapotranspiration.

In earlier work, Hewlett (1961) proposed an explanation of baseflow which envisages the entire soil mantle as a storage aquifer feeding sus-

tained flow. According to this view, narrow groundwater bodies along stream channels are a conduit through which slowly draining soil moisture passes to enter the stream. This is in contrast to the role of groundwater bodies as the source of baseflow from less steep watersheds.

Hewlett's explanation of the source of baseflow in steep watersheds can be described in terms of the physics of saturated-unsaturated flow in soils. Stephenson and Freeze (1974) have developed a two-dimensional transient mathematical model of the saturated-unsaturated subsurface flow through an instrumented cross-section in the Reynolds Creek Experimental Watershed near Boise, Idaho. Their main conclusion was that "transient saturated-unsaturated subsurface flow can deliver snowmelt infiltration through high-

permeability low-porosity formations fast enough to be the sole generating mechanism of runoff from an upstream source area." Data limitations on the Entiat watersheds precluded the use of a complex analysis similar to that of Stephenson and Freeze. In addition, the difficulty in accounting for inhomeogeneities in the hydraulic properties of soils limits the predictive capability of such rigorous techniques applied to real systems (Gardner, 1959).

### **Streamflow**

Channel precipitation, interflow, and surface runoff are summed to obtain the computed streamflow at the stream gage at the bottom of the watershed. No routing of streamflow is necessary since the travel time within each watershed is less than the model time increment of one day.



## CHAPTER V

### VERIFICATION OF THE MODEL

Model verification includes calibration of the model to a particular area, testing the sufficiency of processes defined in the model, and examination of the predictive performance of the model. Because of the inadequacy of the precipitation input information, the following objectives were established for the model verification procedure:

1. To account for the major portion of the initial variance in the streamflow time series;
2. To achieve the correct timing of the annual snowmelt; and
3. To obtain an approximate water balance over the study period.

At various stages a version of the self-calibrating or optimization algorithm described in Figure 18 was applied (Hill et al., 1971). Under this procedure each unknown model parameter is assigned an initial value, an upper and low bound, and a number of increments to cover the range. The first selected parameter is varied through the specified range while all other parameters remain at their initial values. The values of the objective function (measure of error) for each value of the parameters are printed, and the value of the parameter which produced the minimum objective function is stored. After completion of the runs for the first parameter, the second parameter is taken through the same procedure. After all parameters have been varied, the set of values which produced each local minimum is run and the resultant objective function value is compared with the smallest attained in all previous

runs. The vector (values of the parameters) which produced the minimum objective function value is selected as the initial vector for the next phase, and the process is repeated until a parameter vector is found which produces a reasonable correspondence between computed and observed outflows (Hill et al., 1971).

Input to the USUWSM model of this study was daily precipitation and temperature, and output was daily streamflow which may be compared with historical flows. A rough fit first was made using estimated parameter values and initial conditions. Gross adjustments then were made manually before applying the optimization procedure to fix the remaining slack parameter values. A continuous record then was computed to verify the model. When aberrations in output persisted, adjustments were made to the model structure. Table 1 indicates the model parameter values which were established for both pre-fire and post-fire conditions on each of the three study drainage areas.

Two important structural changes were made to the original USUWSM model. As described in the previous chapter, the subsurface component of the model was revised to represent baseflow sustained by unsaturated flow in the earth mantle. A second major alteration to the model was needed because of the importance of snow in the study area. A less sophisticated snowmelt relationship which was used in earlier studies was replaced by the modeling procedure which also was described in the previous chapter. The procedure now used includes groundmelt and freewater in the snowpack which has an important role in the snowmelt process.

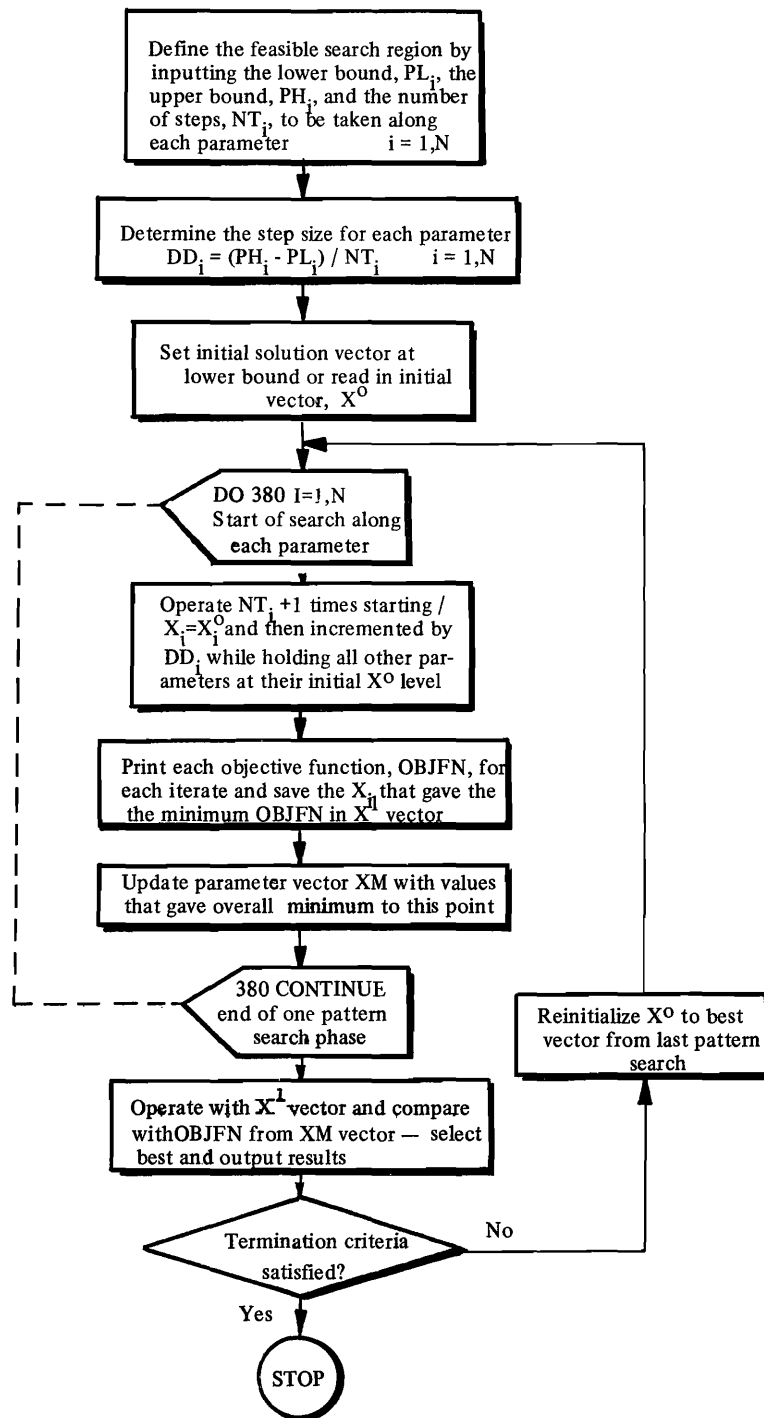


Figure 18. Search algorithm for calibration of hydrologic model (after Hill et al., 1971).

Table 1. Model parameter values for pre-fire and post-fire conditions on the three study watersheds.<sup>1</sup>

Symbol Report	Program	Description	McCree Pre- fire	McCree Post- fire	Burns Pre- fire	Burns Post- fire <sup>2</sup>	Fox Pre- fire	Fox Post- fire
T <sub>s</sub>	TS	Temperature below which all precipitation treated as snow (°F)	30	} UNCHANGED				
T <sub>r</sub>	TR	Temperature above which all precipitation treated as rain (°F)	38					
S <sub>i</sub>	SI	Interception storage capacity (ins)	.2	.02	.2	.08	.2	.14
k <sub>s</sub>	TSW	Decay constant for surface runoff and channel precipitation; each represented as a linear reservoir	1	1	1	1	1	1
T <sub>m</sub>	TMELT	Temperature at which snow melts (°F)	36	32	36	32	36	32
k <sub>m</sub>	SMR	Snowmelt coefficient (ins/°F-day)	.07	.10	.07	.10(.07)	.05	.10
SNGM	SNGM	Daily groundwater melt from snowpack (ins/day)	.01	.01	.01	.01	.01	.01
RI	RAD(M)	Radiation index for m <sup>th</sup> month						
		<u>M</u>						
		Oct. 10	.59	} UNCHANGED THROUGHOUT				
		Nov. 11	.56					
		Dec. 12	.54					
		Jan. 1	.54					
		Feb. 2	.56					
		Mar. 3	.59					
		Apr. 4	.58					
		May 5	.56					
		June 6	.54					
		July 7	.54					
		Aug. 8	.56					
		Sept. 9	.58					
f <sub>o</sub>	FO	Incremental infiltration rate (ins/day)	3	.5	3	.5(1)	3	.5
f <sub>c</sub>	FC	Equilibrium infiltration rate (ins/day)	.5	.5	.5	.5	.5	.5

<sup>1</sup>°F = 9/5 °C + 32, 1 in. = 25.4 mm

<sup>2</sup>Post-fire parameter values in parenthesis were developed by considering the pre-fire period under post-fire conditions. Other post-fire parameter values were developed using the post-fire period only.



Table 1. cont.

Report	Symbol Program	Description	McCree		Burns		Fox	
			Pre- fire	Post- fire	Pre- fire	Post- fire <sup>2</sup>	Pre- fire	Post- fire
CP(m)	CP(M)	Consumptive use for m <sup>th</sup> month (ins/ °F)						
		$\frac{M}{10}$						
		Oct.	.030	.020	.030	.020(.014)	.030	.030
		Nov.	.010	.010	.010	.010(.009)	.010	.010
		Dec.	.000	.000	.000	.000	.000	.000
		Jan.	.000	.000	.000	.000	.000	.000
		Feb.	.000	.000	.000	.000	.000	.000
		Mar.	.000	.000	.000	.000	.000	.000
		Apr.	.010	.010	.010	.010(.009)	.010	.010
		May	.050	.020	.050	.030(.038)	.050	.040
		June	.090	.020	.090	.040(.066)	.090	.070
		July	.100	.020	.100	.040(.076)	.100	.080
		Aug.	.090	.020	.090	.040(.066)	.090	.070
		Sept.	.050	.020	.090	.030(.038)	.090	.040
M <sub>ss</sub>	SS	Saturated soil moisture storage (ins)	15	15	20	20	20	20
M <sub>cs</sub>	SFC	Soil moisture retention capacity (ins)	6	6	6	6	6	6
M <sub>es</sub>	WILT	Soil moisture critical point (ins)	2	2	2	2	2	2
k <sub>b</sub>	BK	The proportion of AVSM that becomes baseflow	.0010	.0010	.0017	.0017	.0018	.0018
k <sub>i</sub>	QK	The proportion of outflow from detention storage which becomes interflow	.14	.14	.15	.15	.16	.16
k <sub>g</sub>	TGW	Decay constant for soil moisture excess treated as in linear reservoir	.10	.10	.08	.08	.08	.08

<sup>2</sup>Post-fire parameter values in parenthesis were developed by considering the pre-fire period under post-fire conditions. Other post-fire parameter values were developed using the post-fire period only.

## CHAPTER VI

### RESULTS

#### Pre-fire

Table 2 summarizes the results of the model study for the pre-fire period. Table 3 contains definitions

for abbreviations used in the sample outputs. As shown by Table 2, if the mean error in prediction of the annual runoff is expressed as a percentage of mean annual runoff, the results for the three drainage areas are as

**Table 2. Summary of calibration results for pre-fire period.<sup>1</sup>**

Year	McCree			Burns			Fox		
	ER	AE	GWR	ER	AE	GWR	ER	AE	GWR
1963	-.46	1.50	-3.379	-.62	1.70	-3.201	-.71	1.84	-4.106
1964	.02	.84	1.116	-.22	1.10	1.497	-.04	1.52	.641
1965	.35	1.21	-4.199	.05	1.52	-4.025	.32	1.52	-5.059
1966	-.39	.90	5.137	-.72	1.05	5.680	-.83	1.37	4.855
1967	.53	1.46	3.872	.80	2.57	4.222	1.65	3.41	3.439
1968	.35	2.70	-10.715	.38	2.93	-10.791	1.74	3.67	-12.079
1969	.38	2.07	-4.159	1.07	2.51	-3.822	2.65	3.39	4.936
1970	.97	1.11	16.950	1.22	1.61	17.831	1.61	1.89	17.613
Total	1.75	11.79	4.623	1.96	14.99	7.391	6.39	18.61	0.368
Mean	0.22	1.47		0.24	1.87		0.80	2.33	
Mean ER / Mean Runoff	5.15%	34.43%		3.95%	30.76%		11.25%	32.77%	

<sup>1</sup> All units are inches (1 in. = 25.4 mm)

$Q_i$  = observed streamflow on  $i^{\text{th}}$  day of year

$QP_i$  = predicted streamflow on  $i^{\text{th}}$  day of year

ER =  $\sum_i (Q_i - QP_i)$  i.e. the error in prediction of annual streamflow

AE =  $\sum_i |(Q_i - QP_i)|$  i.e. the absolute error in prediction of daily runoff for one year. AE was used as an objective function in the optimization algorithm and may be interpreted as a measure of the distribution of error between computed and observed hydrographs.

GWR = Net withdrawal from the zone of percolation summed over one year.  $GWR < 0$  for net inflow (recharge) to the zone of percolation.  $GWR > 0$  for net outflow (withdrawal) from the zone of percolation. The total GWR is a measure of the water balance over the pre-fire study period.



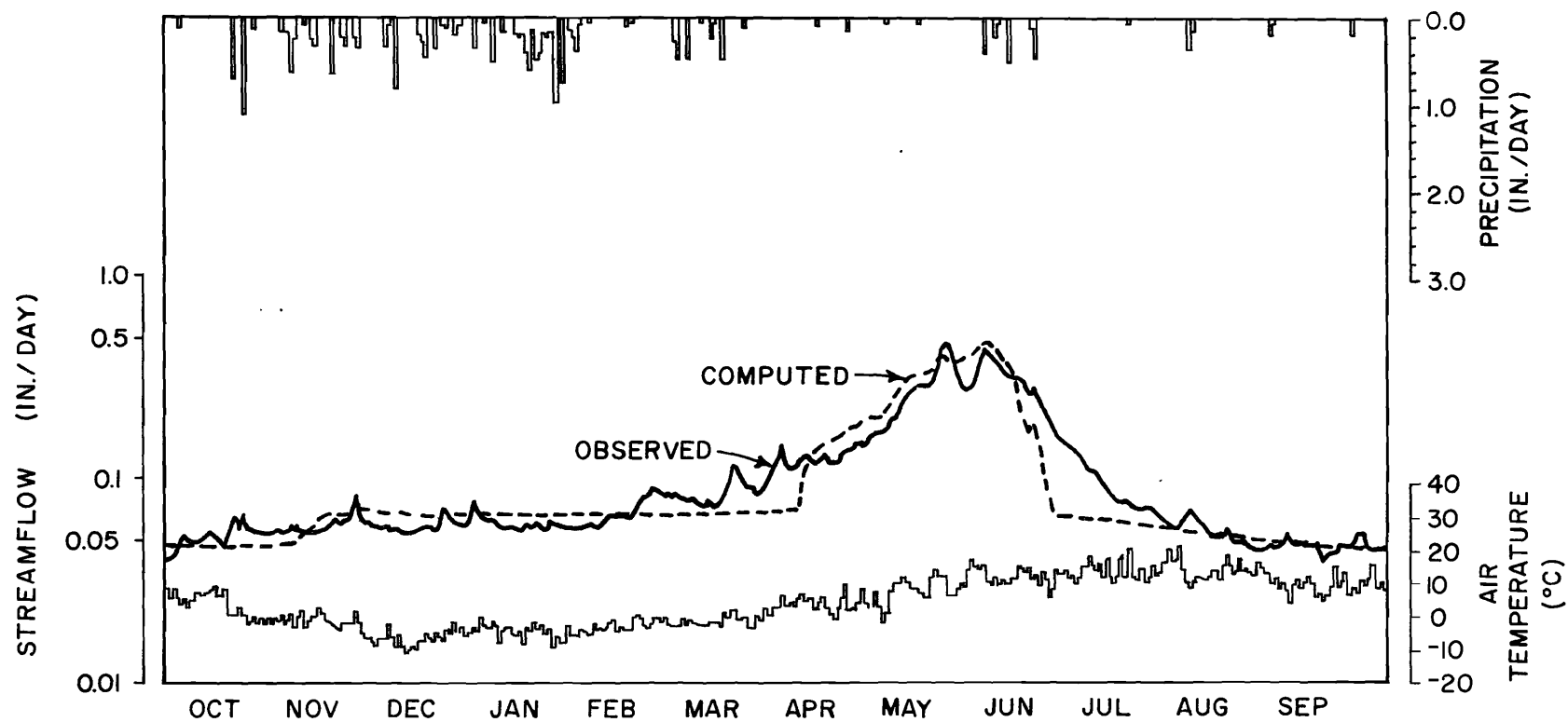


Figure 19. Hydrographs of observed and computed pre-fire streamflow on McCree Creek for the water year 1964 (see Table 4) (1 in. = 25.4 mm,  $^{\circ}\text{C} = 5/9 (^{\circ}\text{F} - 32)$ ).

Table 4. Pre-fire simulation: tabular output for McCree watershed for water year 1964.<sup>1</sup>

MONTHLY WATER BALANCE													
10	PPT	2.61	STM	.16	TEM	36.37	LOSS	2.44	RN	.79	SN	1.81	
11	PPT	4.35	STM	.18	TEM	29.01	LOSS	4.16	RN	.70	SN	3.64	
12	PPT	3.57	STM	.18	TEM	20.42	LOSS	3.38	RN	.00	SN	3.57	
1	PPT	5.11	STM	.19	TEM	23.72	LOSS	7.91	RN	.00	SN	8.11	
2	PPT	.71	STM	.21	TEM	27.09	LOSS	.49	RN	.01	SN	.69	
3	PPT	2.43	STM	.29	TEM	30.43	LOSS	2.13	RN	.11	SN	2.31	
4	PPT	.41	STM	.41	TEM	39.86	LOSS	-.00	RN	.35	SN	.05	
5	PPT	.16	STM	.96	TEM	50.70	LOSS	-.80	RN	.16	SN	.00	
6	PPT	1.96	STM	.84	TEM	53.91	LOSS	1.11	RN	1.96	SN	.00	
7	PPT	.12	STM	.25	TEM	60.17	LOSS	-.13	RN	.12	SN	.00	
8	PPT	.80	STM	.17	TEM	55.52	LOSS	.62	RN	.80	SN	.00	
9	PPT	2.89	STM	.15	TEM	48.93	LOSS	2.73	RN	2.89	SN	.00	
YEARLY WATER BALANCE													
1964	PPT	28.11	STM	4.03	TEM	39.65	LOSS	24.08	RN	7.91	SN	20.20	
HYDROLOGIC DATA--MODEL OUTPUT													
10	SI	.48	SN	1.74	SM	5.67	GW	-1.64	EP	1.15	AV	1.15	
	SR	.00	IF	.00	BF	.15	PF	.15	ER	.01	AE	.02	VR .00
11	SI	.41	SN	4.05	SM	6.15	GW	.14	EP	.29	AV	.29	
	SR	.00	IF	.03	BF	.15	RF	.18	ER	-.00	AE	.02	VR .00
12	SI	.00	SN	8.04	SM	6.09	GW	.31	EP	.00	AV	.00	
	SR	.00	IF	.05	BF	.16	RF	.21	ER	-.03	AE	.03	VR .00
1-1964	SI	.00	SN	16.04	SM	6.09	GW	.26	EP	.00	AV	.00	
	SR	.00	IF	.04	BF	.17	RF	.21	ER	-.02	AE	.02	VR .00
2	SI	.01	SN	16.44	SM	6.09	GW	.24	EP	.00	AV	.00	
	SR	.00	IF	.04	BF	.16	PF	.20	ER	.01	AE	.03	VR .00
3	SI	.42	SN	18.53	SM	6.09	GW	.26	EP	.00	AV	.00	
	SR	.00	IF	.04	BF	.18	RF	.22	ER	.06	AE	.06	VR .00
4	SI	.32	SN	15.52	SM	7.13	GW	1.78	EP	.39	AV	.39	
	SR	.00	IF	.26	BF	.17	PF	.44	ER	-.03	AE	.12	VR .00
5	SI	.15	SN	1.92	SM	10.09	GW	7.45	EP	2.53	AV	2.53	
	SR	.00	IF	.03	BF	.19	RF	1.13	ER	-.16	AE	.20	VR .00
6	SI	1.01	SN	.00	SM	4.85	GW	3.76	EP	4.85	AV	4.85	
	SR	.00	IF	.49	BF	.21	PF	.70	ER	.14	AE	.22	VR .00
7	SI	.11	SN	.00	SM	2.87	GW	-3.91	EP	6.01	AV	6.01	
	SR	.00	IF	.00	BF	.19	RF	.19	ER	.05	AE	.05	VR .00
8	SI	.03	SN	.00	SM	3.26	GW	-4.59	EP	4.99	AV	4.99	
	SR	.00	IF	.00	BF	.17	RF	.17	ER	.00	AE	.01	VR .00
9	SI	.49	SN	.00	SM	6.65	GW	-3.11	EP	2.44	AV	2.44	
	SR	.00	IF	.01	BF	.14	RF	.15	ER	-.00	AE	.01	VR .00
ANNUAL	RF	4.01	ER	.02	AE	.84	GWR	1.116	PE	22.68	SI	4.09	AV 22.68

<sup>1</sup>See Figure 13 and also Table 3 for definition abbreviations used above. TEM is in °F (°F = 9/5 °C + 32). All other units are inches (1 in. = 25.4 mm).

Throughout the study period the model indicated that actual evapotranspiration was equal to potential evapotranspiration. The reason for this was that soil moisture was supplemented by water from the unsaturated zone below the plant roots and hence potential evapotranspiration requirements were always satisfied. Average annual evapotranspiration as predicted by the model was about 23 inches (580 mm). In the simulation of pre-fire years no surface runoff occurred. Some care must be exercised, however, when examining the model predictions for such internal processes as evapotranspiration and surface runoff. The model results can provide only a general picture of the internal processes since no data on these processes were available as a check. In other words, the model of this study is verified only on the basis of streamflow. For example, it is likely that during the late summer when temperatures are high and precipitation is sparse, actual evapotranspiration is less than potential evapotranspiration due to the limiting effect of soil moisture (Helvey, 1973).

### Post-fire

One of the advantages of a simulation model is that the effect on streamflow of changes in watershed characteristics may be investigated with considerable ease and economy. These effects are studied by making changes to model parameters to represent the changes in watershed characteristics. Model output using the new parameter values shows the predicted effects on the streamflow of the watershed alterations. Examples of these watershed changes are the introduction of a reservoir, channel improvements, urbanization, diversions, and vegetation management.

For this study, Table 1 shows the changes made to model parameters for the post-fire simulation. In the table post-fire parameter values shown in parenthesis were obtained for the pre-fire period of data under assumed post-fire conditions; other post-fire parameter values were developed using the post-fire period of data. These changes were to parameters related to watershed characteristics that were affected by the fire.

In a similar study (Fleming, 1971) of two extensively burned watersheds in California, evapotranspiration and interception storage related parameters were reduced to account for streamflow changes. In establishing values of monthly evapotranspiration per °F (CP) and interception storage ( $S_i$ ) Fleming assumed the complete elimination of vegetation from the two watersheds. In the case of the Entiat study, it was estimated from field observations that vegetation cover on the McCree, Burns, and Fox Creek watersheds were 100 percent, 70 percent, and 30 percent destroyed, respectively. Post-fire values for CP and  $S_i$  then were calculated by interpolation between the

estimated values for pre-fire conditions and those for complete vegetation removal, according to the percentage of vegetation destroyed. Berndt (1971), commenting on the effects of the Entiat forest fire, stated "that a reduction of evaporation from the soil by a deep ash mulch could have influenced streamflow after the fire."

Other parameter changes required for post-fire conditions were to the snowmelt coefficient and the incremental infiltration rate. In the absence of a forest canopy an increased quantity of solar energy will reach the snowpack surface. Previous studies (Riley and Chadwick, 1967; U.S. Army Corps of Engineers, 1956; and U.S. Army Corps of Engineers, 1960) indicate a relationship between the vegetation canopy density ( $C_v$ ) and the snowmelt coefficient ( $k_m$ ), such that:

$$k_m = C \exp(-4C_v) \quad \dots \quad (29)$$

where  $C$  is a proportionality constant. Hence, in this study to represent post-fire conditions, the snowmelt coefficient ( $k_m$ ) was increased, and the temperature at which snowmelt occurs ( $T_m$ ) was reduced.

Klock (1971) has observed that "since the fire considerable carbonized plant material (ash) covers the soil surface, particularly in the stream zones." The incremental infiltration rate,  $f_o$ , was reduced to represent the sealing effect of ash on the soil surface (Figure 14). Settergren (1967) indicates that a reduction in infiltration rate is a usual result of forest fires in areas of coarse soils. The fine ash resulting from the fire is washed into the soil pores, and then becomes compacted by raindrop impact. Thus, because the total infiltration value is reduced, the responsiveness of the hydrologic system is increased.

Figure 20 contains hydrographs of observed pre-fire streamflow and computed post-fire streamflow on Burns Creek for the 1964 water year (see also Tables 5 and 6). The difference between the two hydrographs represents the predicted change in streamflow as a result of the fire. Because differences usually are more reliable than absolute values, the computed post-fire streamflow hydrograph was obtained by adding the algebraic difference between the simulated post-fire and simulated pre-fire runoff hydrographs to the observed pre-fire runoff hydrographs.

Due to the short period of data available for calibration of post-fire conditions, the results of the post-fire simulation should be viewed qualitatively rather than quantitatively. The model results indicate a slight increase in the responsiveness of streamflow

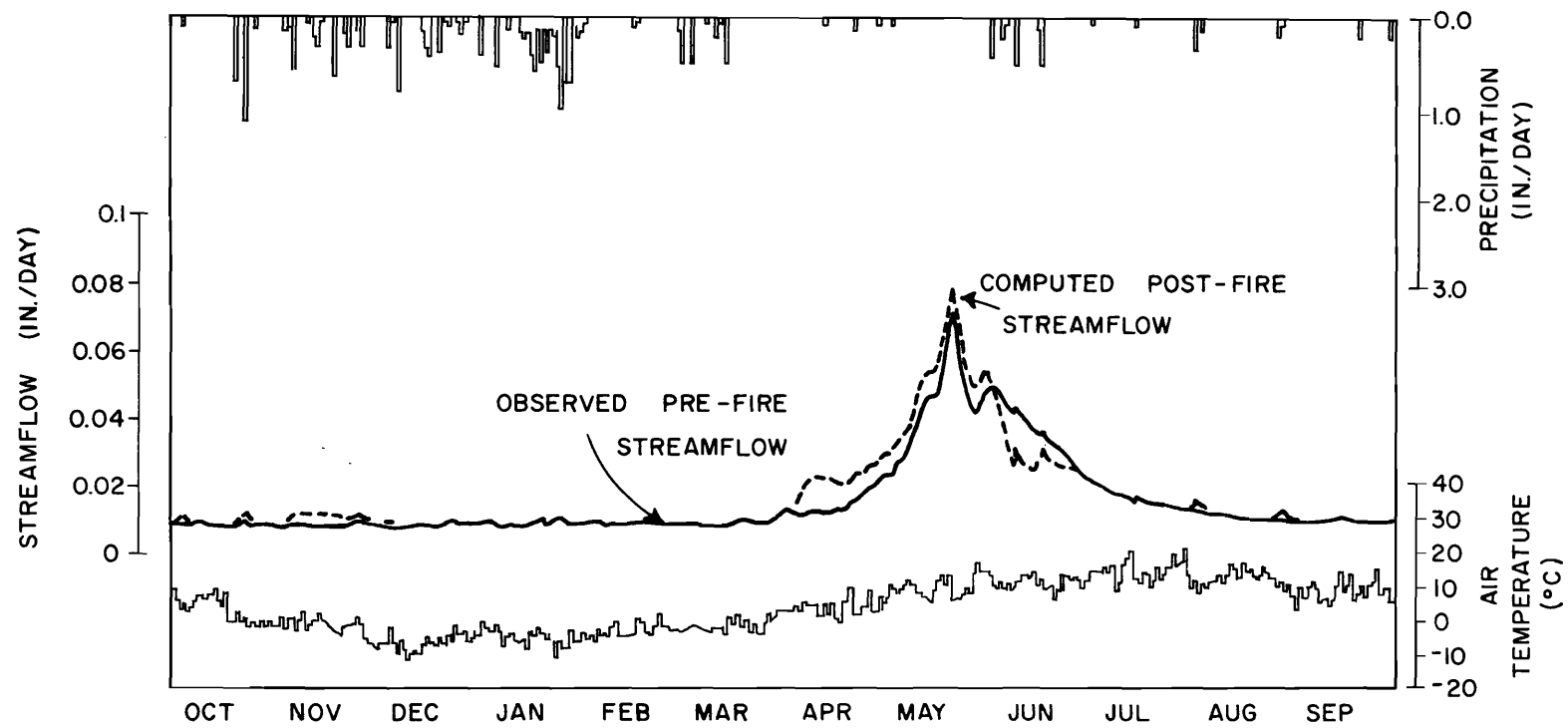


Figure 20. Hydrographs of observed pre-fire streamflow and computed post-fire streamflow on Burns Creek for water year 1964 (see Tables 5 and 6) (1 in. = 25.4 mm,  $^{\circ}\text{C} = 5/9 (^{\circ}\text{F} - 32)$ ).

Table 5. Pre-fire simulation: tabular output for Burns watershed for water year 1964.<sup>1</sup>

MONTHLY WATER BALANCE														
10	PPT	2.75	STM	.26	TEM	37.87	LOSS	2.48	RN	.68	SN	2.06		
11	PPT	4.02	STM	.26	TEM	28.41	LOSS	4.35	RN	.59	SN	4.02		
12	PPT	3.72	STM	.26	TEM	19.92	LOSS	3.45	RN	.80	SN	3.72		
1	PPT	3.48	STM	.27	TEM	23.22	LOSS	8.20	RN	.80	SN	8.48		
2	PPT	2.73	STM	.25	TEM	26.59	LOSS	.47	RN	.91	SN	.72		
3	PPT	2.58	STM	.25	TEM	30.83	LOSS	2.29	RN	.18	SN	2.47		
4	PPT	.45	STM	.44	TEM	39.46	LOSS	.01	RN	.37	SN	.07		
5	PPT	.15	STM	1.36	TEM	50.30	LOSS	-1.20	RN	.16	SN	.00		
6	PPT	2.05	STM	1.08	TEM	53.61	LOSS	.98	RN	2.05	SN	.00		
7	PPT	.12	STM	.49	TEM	59.87	LOSS	-.37	RN	.12	SN	.00		
8	PPT	.84	STM	.33	TEM	55.22	LOSS	.50	RN	.84	SN	.00		
9	PPT	3.02	STM	.27	TEM	48.43	LOSS	2.74	RN	3.02	SN	.00		
YEARLY WATER BALANCE														
1964	PPT	20.41	STM	5.68	TEM	39.41	LOSS	23.91	RN	7.96	SN	21.55		
HYDROLOGIC DATA--MODEL OUTPUT														
10	SI	.25	SI	1.02	SM	5.92	GH	-1.63	EP	1.13	AV	1.13		
SR	.00	TF	.20	BF	.27	RF	.27	ER	-.01	AE	.01	VR	.00	
11	SI	.01	SI	5.65	SM	6.18	GH	-.01	EP	.28	AV	.28		
SR	.00	TF	.01	BF	.25	RF	.25	ER	-.02	AE	.02	VR	.00	
12	SI	.01	SI	0.17	SM	1.11	GH	.25	EP	.00	AV	.06		
SR	.00	TF	.04	BF	.28	RF	.33	ER	-.07	AE	.07	VR	.00	
1-1964	SI	.01	SI	17.23	SM	6.12	GH	.26	EP	.00	AV	.06		
SR	.00	TF	.04	BF	.29	RF	.34	ER	-.06	AE	.06	VR	.00	
2	SI	.01	SI	17.07	SM	6.12	GH	.24	EP	.00	AV	.06		
SR	.00	TF	.04	BF	.29	RF	.32	ER	-.07	AE	.07	VR	.00	
3	SI	.00	SI	16.40	SM	6.12	GH	.24	EP	.00	AV	.06		
SR	.00	TF	.04	BF	.31	RF	.35	ER	-.06	AE	.07	VR	.00	
4	SI	.03	SI	17.00	SM	7.94	GH	1.51	EP	.39	AV	.39		
SR	.00	TF	.25	BF	.30	RF	.55	ER	-.11	AE	.12	VR	.00	
5	SI	.12	SI	17.73	SM	10.74	GH	6.72	EP	2.51	AV	2.51		
SR	.00	TF	.04	BF	.34	RF	1.20	ER	.07	AE	.20	VR	.00	
6	SI	1.02	SI	.00	SM	5.43	GH	5.50	EP	4.82	AV	4.82		
SR	.00	TF	.78	BF	.37	RF	1.11	ER	-.04	AE	.27	VR	.00	
7	SI	.11	SI	.00	SM	3.00	GH	-3.43	EP	5.98	AV	5.98		
SR	.00	TF	.10	BF	.36	RF	.35	ER	.13	AE	.13	VR	.00	
8	SI	.08	SI	.00	SM	3.32	GH	-4.44	EP	4.97	AV	4.97		
SR	.00	TF	.00	BF	.30	RF	.30	ER	.02	AE	.02	VR	.00	
9	SI	.48	SI	.00	SM	6.64	GH	-3.05	EP	2.42	AV	2.42		
SR	.00	TF	.01	BF	.25	RF	.27	ER	.02	AE	.01	VR	.00	
ANNUAL	RF	5.63	ER	-.22	AE	1.10	GWR	1.407	PE	22.53	SI	4.31	AV	22.53

Table 6. Post-fire simulation: tabular output for Burns watershed for water year 1964.<sup>1</sup>

MONTHLY WATER BALANCE														
10	PPT	2.75	STM	.26	TEM	37.87	LOSS	2.48	RN	.68	SN	2.06		
11	PPT	4.02	STM	.26	TEM	28.41	LOSS	4.35	RN	.59	SN	4.02		
12	PPT	3.72	STM	.26	TEM	19.92	LOSS	3.45	RN	.80	SN	3.72		
1	PPT	3.48	STM	.27	TEM	23.22	LOSS	8.20	RN	.80	SN	8.48		
2	PPT	.73	STM	.25	TEM	26.59	LOSS	.47	RN	.91	SN	.72		
3	PPT	2.58	STM	.28	TEM	30.83	LOSS	2.29	RN	.18	SN	2.47		
4	PPT	.45	STM	.44	TEM	39.46	LOSS	.01	RN	.37	SN	.07		
5	PPT	.15	STM	1.36	TEM	50.30	LOSS	-1.28	RN	.16	SN	.00		
6	PPT	2.05	STM	1.08	TEM	53.61	LOSS	.98	RN	2.05	SN	.00		
7	PPT	.12	STM	.49	TEM	59.87	LOSS	-.37	RN	.12	SN	.00		
8	PPT	.84	STM	.33	TEM	55.22	LOSS	.50	RN	.84	SN	.00		
9	PPT	3.02	STM	.27	TEM	48.43	LOSS	2.74	RN	3.02	SN	.00		
YEARLY WATER BALANCE														
1964	PPT	20.41	STM	5.68	TEM	39.41	LOSS	23.91	RN	7.96	SN	21.55		
HYDROLOGIC DATA--MODEL OUTPUT														
10	SI	.25	SI	1.02	SM	5.91	GH	-1.05	EP	.90	AV	.90		
	SR	.00	TF	.20	BF	.28	RF	.29	ER	-.03	AE	.03	VR	.00
11	SI	.26	SI	5.45	SM	6.18	GH	.35	EP	.25	AV	.25		
	SR	.02	TF	.06	BF	.28	RF	.35	ER	-.09	AE	.09	VR	.00
12	SI	.04	SI	0.86	SM	6.12	GH	.31	EP	.00	AV	.00		
	SR	.00	TF	.05	BF	.30	RF	.35	ER	-.09	AE	.09	VR	.00
1-1964	SI	.00	SI	17.43	SM	6.12	GH	.26	EP	.00	AV	.00		
	SR	.00	TF	.04	BF	.30	RF	.35	ER	-.07	AE	.07	VR	.00
2	SI	.01	SI	17.46	SM	6.12	GH	.24	EP	.00	AV	.00		
	SR	.00	TF	.04	BF	.29	RF	.33	ER	-.07	AE	.07	VR	.00
3	SI	.00	SI	19.70	SM	6.12	GH	.26	EP	.00	AV	.00		
	SR	.00	TF	.04	BF	.31	RF	.36	ER	-.07	AE	.07	VR	.00
4	SI	.25	SI	14.65	SM	7.94	GH	2.90	EP	.35	AV	.35		
	SR	.00	TF	.26	BF	.31	RF	.78	ER	-.33	AE	.34	VR	.00
5	SI	.15	SI	.00	SM	10.91	GH	8.80	EP	1.91	AV	1.91		
	SR	.00	TF	1.10	BF	.36	RF	1.52	ER	-.15	AE	.25	VR	.00
6	SI	.48	SI	.00	SM	5.47	GH	3.41	EP	3.53	AV	3.53		
	SR	.00	TF	.50	BF	.38	RF	.91	ER	.15	AE	.23	VR	.00
7	SI	.09	SI	.00	SM	3.71	GH	-2.67	EP	4.55	AV	4.55		
	SR	.00	TF	.00	BF	.36	RF	.36	ER	.12	AE	.12	VR	.00
8	SI	.33	SI	.00	SM	4.10	GH	-3.20	EP	3.64	AV	3.64		
	SR	.00	TF	.00	BF	.32	RF	.33	ER	.00	AE	.01	VR	.00
9	SI	.23	SI	.00	SM	6.20	GH	-2.20	EP	1.84	AV	1.84		
	SR	.77	TF	.00	BF	.28	RF	1.08	ER	-.80	AE	.80	VR	.02
ANNUAL	RF	7.35	ER	-1.46	AE	2.22	GWR	-3.810	PE	17.80	SI	2.36	AV	17.80

<sup>1</sup> See Figure 14 and also Table 3 for definition of abbreviations used above. TEM is in °F (°F = 9/5 °C + 32). All other units are inches (1 in. = 25.4 mm).



to precipitation, with both flood peaks and flood volumes being increased in periods of above-freezing temperatures. Also, post-fire snowmelt occurs earlier in the season and results in higher streamflow rates than

was the case for pre-fire conditions. Fleming (1971), Beatty (1967), and Hansen (1968) have also observed that the removal of vegetation has increased the water yield of watersheds.

## CHAPTER VII

### DISCUSSION, RECOMMENDATIONS, AND CONCLUSIONS

#### Discussion

There are two limitations to be considered when examining the results of a simulation study:

1. The representativeness of the data; and
2. The adequacy of the model structure and calibration.

Data preparation is described at the beginning of this report. Spatial distribution of precipitation was based on stations located approximately 30 miles (48 km) from the study area. Normally, a more reliable distribution would be expected from the gages on the study area. However, the available records from these were too short to derive a meaningful method for distributing the measured precipitation. This situation represents a severe limitation to the simulation study. Streamflow was measured at a single point on each watershed and was therefore considered to be more accurate than estimated precipitation.

Despite the limitation of inadequate data to estimate the spatial distribution of precipitation, reasonable agreement was achieved between observed and simulated streamflow, both in terms of the overall timing and quantity. To achieve these results it was necessary to make some structural changes to the Utah State University Watershed Simulation Model (USUWSM). In particular, changes were made in the representations of the subsurface hydrology and snowmelt processes. In addition, changes were made to some of the storages functions as they are affected by evapotranspiration.

With the significant difference in elevation on each of the three study watersheds, it is expected that the representation of the hydrologic system would be improved through the use of a distributed parameter, rather than a lumped parameter, model. In this case, however, the data inadequacy precluded the use of spatially high resolution models.

Post-fire results indicated a slight increase in the responsiveness of streamflow to precipitation with both flood peaks and flood values being increased in

periods of above freezing temperatures. This change can be attributed to two factors, namely (1) reduced evapotranspiration resulting from the destruction of vegetation, and the accumulation of ash on the soil surface, and (2) reduced infiltration rates and consequent increases in overland flow on the post-fire watersheds. Also, post-fire snowmelt occurs earlier and is associated with higher streamflow rates than was the case for pre-fire conditions. This change is due mainly to the loss of shading from vegetation which was removed by the fire. Thus, snowmelt occurs more rapidly than was the case under pre-fire conditions. Because they are based on a very short period of post-fire record, a cautionary note must be applied to the above conclusions on the effects of the fire on the runoff characteristics.

#### Recommendations

As a result of the simulation experience on the Entiat Experimental Watershed, the following recommendations are made:

1. A fairly dense precipitation data network should be established on the experimental watersheds. A period of record of four or five years might be expected to yield a realistic spatial distribution of precipitation in terms of model input.

2. In the light of Hewlett and Hibbert's findings, some further changes to the modified model are proposed. The linear groundwater reservoir removed in the earlier model changes will be replaced. Base percolation will enter the saturated groundwater body close to the stream and outflow from this linear groundwater reservoir will be baseflow. Instead of the indirect method of calculating base percolation from the approximate moving average of soil moisture, the approximate moving average of percolation zone storage itself will be used in Equations 27 and 28. This more flexible model will facilitate investigation of the relative importance of unsaturated flow to the generation of low flows from a particular watershed and will restore the model's internal mass balance. It is considered that it also will improve prediction of the snowmelt hydrograph

recession which was over-dampened in the new model. Figure 21 contains a comparison of the initial, new (current), and proposed models.

3. A hydrogeological investigation is recommended into the subsurface water regime of the study area. This investigation should be aimed at achieving a better understanding of the causative factors associated with the unresponsiveness of streamflow to precipitation. Special attention should be given to identifying saturated and unsaturated subsurface zones and to the measurement of soil moisture tension variation with time and elevation. These data either would help to confirm that baseflow is sustained by unsaturated flows in the earth or would provide an alternative explanation.

4. As post-fire data continues to accumulate, it will be possible to further check and improve the simulation of post-fire conditions, and also to study the dynamic effects of vegetation regrowth on streamflow characteristics.

## Conclusions

The study has demonstrated the potential utility of the simulation approach for investigating the physical processes behind changes in runoff characteristics resulting from the effects of fire and other possible management changes on a forest watershed. In this regard, Figure 22 demonstrates the development process of a hydrologic model. It is a continuous process which includes feedback loops. Several of the loops shown in Figure 22 were utilized in this study. In particular, the improvement of system definition was necessary in the subsurface and snow models. The modeling effort has shown data deficiencies for establishing a precipitation distribution relationship and for calibrating the watershed under post-fire conditions. Also, this study has shown a need for a better understanding of the subsurface flow regime of the experimental watershed. As these data and knowledge deficiencies at the study area are satisfied, and as fire-hydrology relationships become better understood, the predictive capability of the USUWSM as applied to this area will be enhanced. Further simulation studies should place greater emphasis on the role of vegetation, and in particular, the post-fire vegetation succession and its effects on hydrologic characteristics.

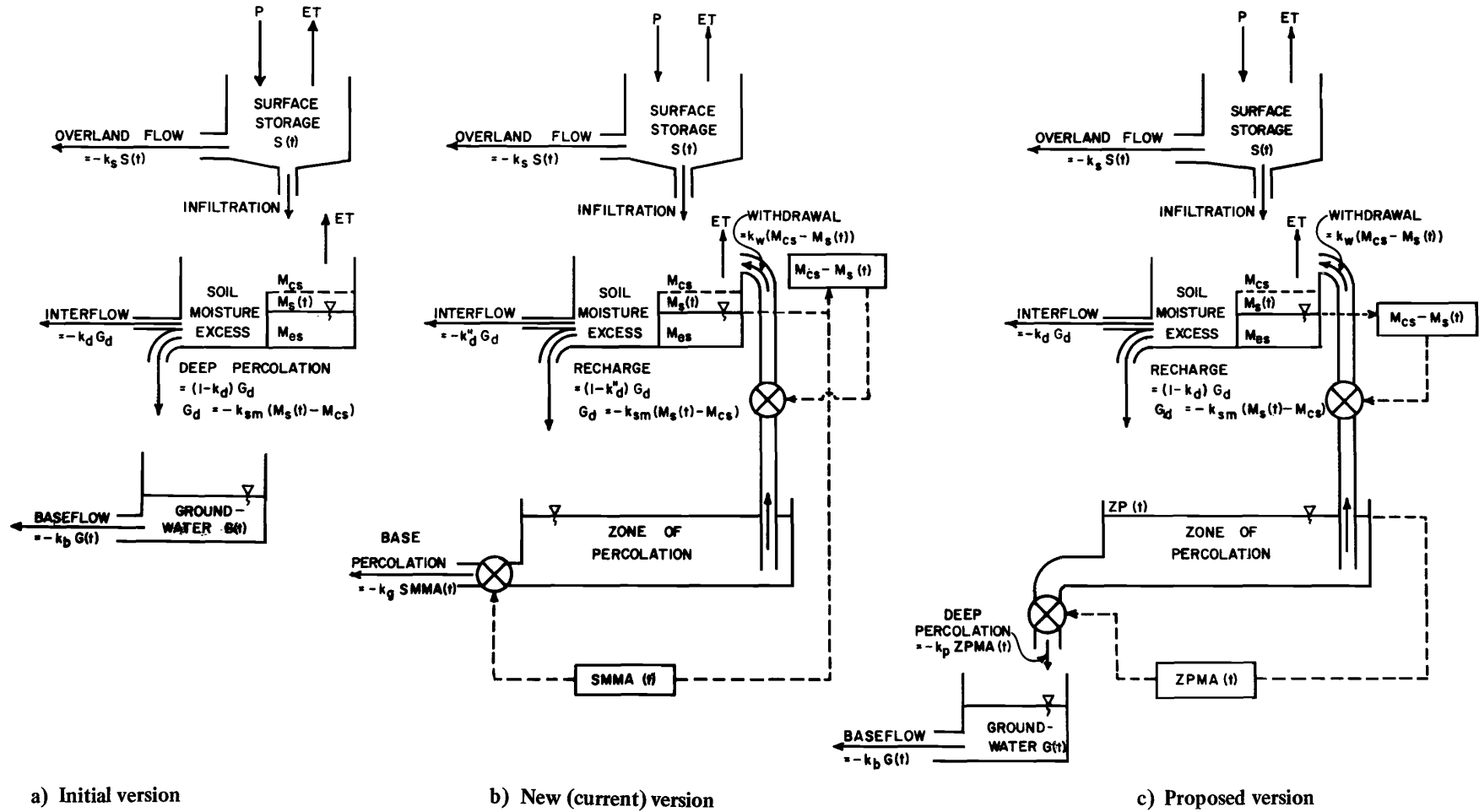


Figure 21. Comparison of the flow diagrams for the initial, new, and proposed versions of the watershed hydrologic model.

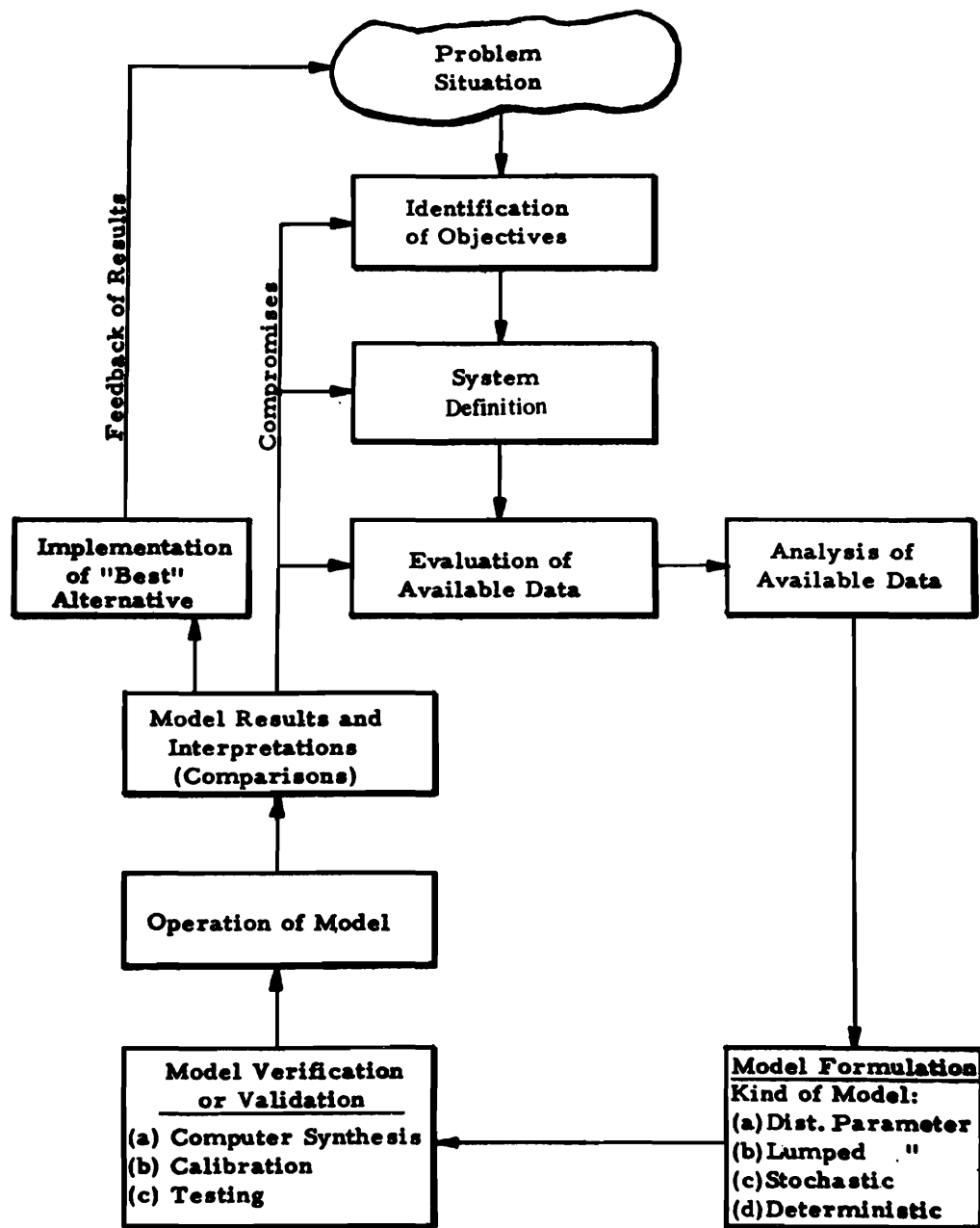


Figure 22. Development process of a hydrologic model (after Riley, 1970).

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## **APPENDIX**

### **Listing of Utah State University Watershed Simulation Model Computer Program**

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C *** MAIN PROGRAM - UTAH STATE UNIVERSITY WATERSHED SIMULATION MODEL
COMMON/BLK1/PRCP(12,31),TEMP(12,31),STRM(12,31),COMP(12,31)
2/BLK2/CP(12),RAD(12),MON(12),SUMN(12),SUMY(8),KW,KR,AREA,TCF
3/BLK3/FTF,CPE,SI,SS,SFC,WILT,FD,FC,SMR,AVD,SNGL,TGW,TSW,TFWSN,
JOK,FK,TRAIN,TMELT,TSNOW,SIO,SNIC,SMOIC,RSW,KTRL,KNTR,SHM,WMM,AVSM,
SCSJ,NYR,MYR,NSW,IYR,KK,ENIC,IMJ,SMIC,CT,IX,IWS
C ** INITIALISE
C KR=READER CONTROL KW=WRITE CONTROL
KR=6
KW=6
MYR=0
NYR=0
1 M=0
40=0
TRAIN=38.
TSNOW=30.
DO 25 I=1,6
25 SUMY(I)=0.
DO 200 I=1,2
200 WRITE(KW,23)
23 FORMAT(1H1,21HMONTHLY WATER BALANCE)
C ** INPUT AND CALCULATE MONTHLY AND ANNUAL WATER BALANCE
PAUSE 1
C * READ 1ST YEAR NO AND WATERSHED NO
IYR=IYR-1961
IF(NYR.GT.1)GOTO 110
READ(KR,10)IYR,IWS
10 FORMAT(2I1)
110 IMJ=12
IF(IYR.EQ.9)IMJ=9
C * READ DAILY CLIMATOLOGICAL AND HYDROLOGIC DATA FOR IYR TH YEAR
CALL DREAD(IYR,IWS)
IYR=IYR+1962
MONTHLY LOOP
DO 22 M=1,IMJ
22 MO=MO+1
IF(MO.EQ.13)MO=1
DO 17 J=1,6
17 SUMN(J)=0.
MDAY=MON(M)
DAILY LOOP
DO 20 I=1,MDAY
20 SUMN(1)=SUMN(1)+PRCP(M,I)
SUMN(2)=SUMN(2)+STRM(M,I)
SUMN(3)=SUMN(3)+TEMP(M,I)
PPT=PRCP(M,I)
SEPARATE RAIN AND SNOW
TEMR=TEMP(M,I)
IF(TEMR-TSNOW)38,38,40
38 SNOW=PPT
PPT=0.0
GO TO 49
40 IF(TEMR-TRAIN)42,42,44
42 SNOW=PRCP(M,I)+(TRAIN-TEMR)/(TRAIN-TSNOW)
PPT=PPT-SNOW
GO TO 49

```

```

C KNTR=2 DAILY OUTPUT AND ALL GRAPHS
C KTRL=1 SINGLE YEAR RUN MANUAL VERIFICATION
C KTRL=2 CONTINUOUS RUN MANUAL VERIFICATION
C KTRL=3 PARAMETER OPTIMIZATION
GO TO (2,3,4),KTRL
C * SINGLE YEAR RUN, MANUAL VERIFICATION
2 CALL HYDRGY
IF(KNTR.EQ.0) GO TO 50
CALL GRAPH
GO TO 50
C * CONTINUOUS RUN, MANUAL VERIFICATION
3 CALL HYDRGY
MYR=MYR+1
IF(KNTR.EQ.0) GO TO 136
CALL GRAPH
136 IF(NYR-MYR)150,150,1
C * PARAMETER OPTIMIZATION
4 CALL HYDRGY
KK=1
CALL OPTVER
MYR=MYR+1
IF(KNTR.EQ.0) GO TO 137
CALL GRAPH
137 IF(NYR-MYR)150,150,1
C ** OPTION OF NEW RUN WITHOUT READING DAILY DATA AND WATERSHED
C CHARACTERISTIC DATA AGAIN
150 WRITE(2,233)
233 FORMAT(18HTYPE 1 FOR NEW RUN)
READ(2,10)ISTOP
MYR=0
IF(ISTOP.EQ.1)GOTO 51
STOP
END

```

```

44 SNOW=0.
49 SUMN(4)=SUMN(4)+PPT
  SUMN(5)=SUMN(5)+SNOW
20 CONTINUE
  SUMN(3)=SUMN(3)/FLOAT(MDAY)
  PLOSS=SUMN(1)-SUMN(2)
  IF (SUMN(5).LE.0.) SUMN(5)=0.
  WRITE(KW,21) MD,SUMN(1),SUMN(2),SUMN(3),PLOSS,SUMN(4),SUMN(5)
21 FORMAT(1X,I4,1X,3HPPT,F5.2,1X,3HSTM,1X,F5.2,1X,3HTEM,1X,F5.2,1X,4H
  1LOSS,1X,F5.2,1X,2HRN,1X,F5.2,1X,2HSN,1X,F5.2)
  SUMY(1)=SUMY(1)+SUMN(1)
  SUMY(2)=SUMY(2)+SUMN(2)
  SUMY(3)=SUMY(3)+SUMN(3)/FLOAT(IMJ)
  SUMY(4)=SUMY(4)+SUMN(4)
22 SUMY(5)=SUMY(5)+SUMN(5)
  YLOSS=SUMY(1)-SUMY(2)
  WRITE(KW,24)
24 FORMAT(1X,20HYEARLY WATER BALANCE)
  WRITE(KW,21) IYR,SUMY(1),SUMY(2),SUMY(3),YLOSS,SUMY(4),SUMY(5)
  IF (NYR.GT.0) GO TO 57
  WRITE(KW,5)
5 FORMAT(1X,29HWATERSHED CHARACTERISTIC DATA)
C * READ WATERSHED CHARACTERISTIC DATA
C 1 AREA
  READ(KR,7) AREA
  WRITE(KW,7) AREA
7 FORMAT(2F10.2)
C 2 MONTHLY RADIATION INDEX
  READ(KR,8) (RAD(M),M=10,12), (RAD(M),M=1,9)
8 FORMAT(4X,12F4.2)
C 3 MONTHLY EVAPORATION INDEX
  READ(KR,9) (CP(M),M=1,12)
9 FORMAT(3X,12F6.3)
  WRITE(KW,6) (CP(M),M=1,12), (RAD(M),M=1,12)
6 FORMAT(2X,2HCP,1X,12F6.5/2X,3HRA,1X,12F5.2)
C * READ MODEL PARAMETERS
  GOTO 50
51 PAUSE 10101
50 READ(KR,39) SIO,SNIC,SMOIC,AVSM,KNTR,KTRL,NYR
  WRITE(KW,39) SIO,SNIC,SMOIC,AVSM,KNTR,KTRL,NYR
39 FORMAT(4F10.4,3I10)
  READ(KR,37) ETF,SI,AVD,SMR,FO,FC,TSW
  WRITE(KR,37) ETF,SI,AVD,SMR,FO,FC,TSW
  READ(KR,37) CPF,WHM,BK,SNHG,TFWSN,THELT
  WRITE(KW,37) CPF,WHM,BK,SNHG,TFWSN,THELT
  READ(KR,37) SS,SFC,WILT,OK,TGW,SHM,TRAIN,TSNOW
  WRITE(KW,37) SS,SFC,WILT,OK,TGW,SHM,TRAIN,TSNOW
37 FORMAT(8F10.4)
57 WRITE(KW,47)
47 FORMAT(1X,29HHYDROLOGIC DATA==MODEL OUTPUT)
C INITIALISE
  ENIC=AVSM
  SMIC=SMOIC
C ** SELECT OPTIONS BY USING CONTROL PARAMETERS KNTR AND KTRL
  KK=0
  NYR=0
C KNTR=0 OUTPUT ONLY MONTHLY SUMMARY
C KNTR=1 DAILY OUTPUT AND COMPUTE HYDROGRAPH

```

```

SUBROUTINE DREAD(IY,IWS)
C *** TO TRANSFER WENATCHEE DATA FROM MAG TAPE TO MAIN SIM PROGRAM
COMMON/BLK1/PRCP(12,31),TEMP(12,31),STRM(12,31),COMP(12,31)
2/BLK2/CP(12),RAD(12),MDN(12),SUMN(12),SUMY(8),KW,KR,AREA,TCF
3/BLK3/ETF,CPF,SI,SS,SFC,WILT,FO,FC,SMR,AVD,SNHG,TGW,TSW,TFWSN,
4OK,BK,TRAIN,THELT,TSNOW,SIO,SNIC,SMOIC,RSW,KTRL,KNTR,SHM,WHM,AVSM,
50BJ,NYR,MYR,NSW,IYR,KK,ENIC,IMJ,SMIC,CT,TX
DOUBLE PRECISION NAME
DATA NAME/6HWDAT/
500 FORMAT(3I2)
513 FORMAT(I2,3(F4.2,F5.1,F6.2))
514 FORMAT(18HINCORRECT ID GEN=,I2,7H READ=,I2)
C ** INITIALISE
  IF (MYR.NE.0) GOTO 5
  CALL OMON(22,13)
  CALL OMON(21,NAME,1,13)
C ** LOCATE REQUIRED YEAR KY
5 READ(13,500) KY,KM,MDN(1)
  IF (KY=IY) 15,25,10
10 CALL OMON(12)
  GOTO 5
15 IMI=12
18 DO 20 IM=1,IMI
  IF (IM.NE.1) READ(13,500) KY,KM,MDN(IM)
  KD2=MDN(IM)
  DO 20 ID=1,KD2
20 READ(13,513) KSKIP
  GOTO 5
C ** READ YEAR KY OF DATA
25 IF (KM.EQ.4) GOTO 28
  IMI=3
  GOTO 18
28 DO 30 IM=1,IMI
  IF (IM.NE.1) READ(13,500) KY,KM,MDN(IM)
  KD2=MDN(IM)
  DO 30 ID=1,KD2
  GOTO(35,40,45),IWS
35 READ(13,513) JD,PRCP(IM,ID),TEMP(IM,ID),STRM(IM,ID)
  GOTO 50
40 READ(13,513) JD,A,B,C,PRCP(IM,ID),TEMP(IM,ID),STRM(IM,ID)
  GOTO 50
45 READ(13,513) JD,A,B,C,A,B,C,PRCP(IM,ID),TEMP(IM,ID),STRM(IM,ID)
  IF (JD.NE.ID) WRITE(1,514) ID,JD
  STRM(IM,ID)=STRM(IM,ID)/1000.0
50 CONTINUE
  RETURN
  END

```

```

SUBROUTINE HYDRGY
C *** FOREST WATERSHED HYDROLOGIC SYSTEM SIMULATION
COMMON/HLK1/PPCP(12,31),TEMP(12,31),STRM(12,31),COMP(12,31)
2/BLK2/CP(12),RAD(12),MDN(12),SUMN(12),SUMY(8),KW,KR,AREA,TCF
3/RLK3/ETF,CPF,SI,SS,SFC,WILT,FO,FC,SHR,AVD,SNOW,TGW,TSM,TFSN,
4QK,KK,TRAIN,TMELT,TSNOW,SIO,SNIC,SMOIC,RSW,KTRL,KNTR,SMM,WHM,AVSM,
5DRJ,NYR,MYR,NSW,IYR,KK,ENIC,IMJ,SMIC,CT,TX,IWS
C ** INITIALISE
MO=0
IF(MYR.EQ.0)GO TO 9
IF(NYR.GT.0)GO TO 51
9 RSW=0.
CPR=0.
SMAY=0.
FT=FC
T1=60.
T2=0.
FWSN=0.
SNRF=0.
51 DO 5 I=1,8
5 SUMY(I)=0.
AVSM=ENIC
SMOIC=SMIC
DO 120 M=1,IMJ
EPH=CP(M)*ETF
SNF=SHR*RAD(M)
MONTHLY LOOP
DO 15 J=1,12
15 SUMN(J)=0.
MDAY=MDN(M)
DAILY LOOP
DO 100 I=1,MDAY
RAIN=0.
OSW=0.
GWR=0.
Z1=0.
SRQ=0.
CHPF=0.
PPT=PRCP(M,I)
C ** SEPARATE RAIN AND SNOW
TEMR=TFMP(M,I)
IF(TEMR-TSNOW)38,38,40
38 SNOW=PRCP(M,I)
PPT=0.0
GO TO 49
40 IF(TEMR-TRAIN)42,42,44
42 SNOW=PRCP(M,I)*(TRAIN-TEMR)/(TRAIN-TSNOW)
PPT=PPT-SNOW
GO TO 49
44 SNOW=0.0
49 COMP(M,I)=0.0
C ** RAIN ON CHANNEL
CHPPT=PPT*CPF+CPR
PPT=PPT*(1.-CPF)
CPR=CHPPT*EXP(-TSW)
CHPF=CHPPT-CPR

```

```

156 IF(Y-SWH-WHC)157,157,158
157 SNRF=((Y-WHC)**2)/(2.0*SWH)
SNIC=SNIC-((Y-WHC)**2)/(2.0*SWH)
GO TO 35
158 SNRF=FWSN-WHC
SNIC=SNIC-SNRF
36 IF(SNIC.GT.0.)GO TO 35
SNRF=SNIC+RAIN+RSW
RAIN=0.
RSW=0.
FWSN=0.
SNIC=0.
GO TO 141
35 WHCE=SNIC*0.05
SNRF=SNRF+(WHC-WHCE)
SNIC=SNIC-(WHC-WHCE)
FWSN=FWSN+WHCE
138 IF(TEQ.GE.32.) GO TO 141
FWSN=FWSN*EXP(-TFWSN*(32.-TEQ))
139 IF(FWSN.LE.0.0)FWSN=0.
GO TO 141
140 SNRF=0.
C ** TOTAL AVAILABLE SURFACE WATER
141 RAIN=RAIN+SNRF+RSW
C ** DETERMINE INFILTRATION RATE
50 IF(RAIN-FC) 64,64,62
62 FT=FC+FO*(SS-SMOIC)/SS
SFW=RAIN-FT
IF(SFW)64,64,66
C ** SOIL MOISTURE STORAGE
64 SMOIC=SMOIC+RAIN
RSW=0.
GO TO 72
66 SMOIC=SMOIC+FT
C ** SURFACE RUNOFF
RSW=SFW*EXP(-TSW)
SRQ=SFW-RSW
SUMN(2)=SUMN(2)+SRQ
C ** EVAPOTRANSPIRATION
72 EVP=TEMP*EPH/FLOAT(MDAY)
SUMN(3)=SUMN(3)+EVP
SUMN(4)=SUMN(4)+EVP
IF(EVP.LT.SIO)GO TO 74
EVP=EVP-SIO
SIO=0.
IF(EVP.LT.SNIC)GO TO 76
EVP=EVP-SNIC
SNIC=0.
IF(SMOIC.GT.WILT)GO TO 92
EEVP=EVP*SMOIC/WILT
SMOIC=SMOIC-EEVP
SUMN(4)=SUMN(4)+EEVP-EVP
GO TO 70
74 SIO=SIO-EVP
GO TO 70
76 SNIC=SNIC-EVP
GO TO 70
92 SMOIC=SMOIC-EVP

```

PAGE 2 C SIMULATION OF FOREST WATERSHED HYDROLOGY. UWRL WG126-1

```

C ** INTERCEPTION
IF (PPT+SNOW) 55,55,11
11 OSI=SI-SIO
IF (PPT-OSI) 52,53,54
52 SIO=SI+PPT
SUMN(1)=SUMN(1)+PPT
RAIN=0.
GO TO 55
53 SIO=SI
SUMN(1)=SUMN(1)+SI
RAIN=0.
GO TO 55
54 SIO=SI
SUMN(1)=SUMN(1)+OSI
RAIN=PPT-OSI
C ** SNOW ACCUMULATION AND MELT
55 IF (SNIC,LT,SNGM) GOTO 1000
SNIC=SNIC-SNGM
SMOIC=SMOIC+SNGM
GOTO 1010
1000 SMOIC=SMOIC+SNIC
SNIC=0.
1010 TEQ=0.1+T1+0.3*T2+0.6*TEMR
T1=T2
T2=TEMR
IF (SNOW,GT,0.) GO TO 31
IF (SNIC,LE,0.) GO TO 140
31 SNIC=SNIC+SNOW
SNICB=SNIC
WHC=SNIC*.35
SDAY=SDAY+1.0
IF (SNOW,NE,0.) SDAY=0.
ALBD=0.40*(1.+EXP(-0.2*SDAY))
IF (RAIN,NE,0.) ALBD=0.4
C * SNOWMELT AMOUNT
SHAM=SNF*(TEQ-TMELT)*(1.-ALBD)+(TEMR-32.0)*1.0*RAIN/144.
IF (SHAM,LE,0.) SHAM=0.
IF (SHAM,LE,SNIC) GOTO 28
SHAM=SNIC
SNIC=0.
SNRF=SHAM
GO TO 141
C * FREE WATER IN SNOW PACK
28 FWSN=FWSN+SHAM+RAIN+RSW
SNIC=SNIC+RAIN+RSW
RSW=0.
RAIN=0.
SWH=WHH+WHF
Y=0.2*SWH+FWSN
IF (Y,LT,0.00001) GOTO 159
Y=SQRT(Y)
PA=Y/SWH
IF (PA,LE,1.0) GOTO 155
Y=F*SN+SWH/2.0
155 IF (Y,GT,WHC) GOTO 156
C * RUNOFF FROM SNOW
159 SNRF=0.
GO TO 138

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C ** INTERFLOW
70 IF (SMOIC-SFC) 150,84,152
150 GSW=SFC-SMOIC
ZI=GSW*SMH
SMOIC=SMOIC+ZI
GOTO 154
152 GSW=SMOIC-SFC
GSI=GSW*EXP(-TGW)
OSW=GSW-GSI
SMOIC=SMOIC-OSW
GWR=(1.-OK*(1.-GSW/SS))*OSW
OSW=OSW-GWR
154 SUMN(5)=SUMN(5)+OSW
SUMN(11)=SUMN(11)+GWR-ZI
C ** BASEFLOW FROM INTERMEDIATE ZONE IN THE ZONE OF AERATION
84 AVSM=(AVSM*(AVD-1.)+SMOIC)/AVD
BF=BK*AVSM
SUMN(6)=SUMN(6)+BF
RUNOFF=(SRD+OSW+BF+CHPF)
C ** MONTHLY SUMMARY
SUMN(7)=SUMN(7)+RUNOFF
ERR=STRM(M,I)-RUNOFF
COMP(M,I)=COMP(M,I)+RUNOFF
SUMN(8)=SUMN(8)+ERR
C * CALCULATE OBJECTIVE FUNCTION
SUMN(9)=SUMN(9)+ABS(ERR)
SUMN(10)=SUMN(10)+ERR*ERR
100 CONTINUE
C ** YEARLY SUMMARY
SUMY(1)=SUMY(1)+SUMN(3)
SUMY(2)=SUMY(2)+SUMN(7)
SUMY(3)=SUMY(3)+SUMN(8)
SUMY(4)=SUMY(4)+SUMN(9)
SUMY(5)=SUMY(5)+(SUMN(6)-SUMN(11))
SUMY(6)=SUMY(6)+SUMN(1)
SUMY(7)=SUMY(7)+SUMN(4)
IF (KK,EQ,1) GO TO 120
MO=MO+1
IF (MO,EQ,12) MO=1
IF (MO,EQ,1) GO TO 103
GO TO 105
C ** OUTPUT SUMMARY REPORTS
103 WRITE (KW,121) MO,IYR
121 FORMAT(1X,I2,1H-,14)
GO TO 106
105 WRITE (KW,101) MO
101 FORMAT(1X,I2)
106 WRITE (KW,102) SUMN(1),SNIC,SMOIC,SUMN(11),SUMN(3),SUMN(4)
102 FORMAT(1X,2H9I,F6.2,2X,2H5N,F6.2,2X,2H5M,F6.2,2X,2H5W,F6.2,2X,
12HEP,F6.2,2X,2HAV,F6.2,5X,2X,F6.2)
WRITE (KW,104) SUMN(2),SUMN(5),SUMN(6),SUMN(7),SUMN(8),SUMN(9),
1SUMN(10)
104 FORMAT(1X,2H5R,F6.2,2X,2HIF,F6.2,2X,2HBF,F6.2,2X,2HRF,F6.2,2X,
12HEP,F6.2,2X,2HAE,F6.2,2X,2HVR,F10.2)
120 CONTINUE
OBJ=SUMY(4)
IF (KK,EQ,1) GO TO 199
WRITE (KW,122) SUMY(2),SUMY(3),SUMY(4),SUMY(6),SUMY(1),SUMY(5),

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      SUMY(7)
127 FORMAT(1X, CHANNEL, PF, F6.2, 2X, 2HER, F6.2, 2X, 2HAE, F6.2, 2X, 3HGW,
180.3, 2X, 2HPE, F6.2, 2X, 2HSI, F6.2, 2X, 2HAV, F6.2 ///)
199 RETURN
      END

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      SUBROUTINE OPTVER
C *** PARAMETER OPTIMIZATION
COMMON/BLK1/PRCP(12,31),TEMP(12,31),STRM(12,31),COMP(12,31)
2/BLK2/CP(12),RAD(12),MDN(12),SUMN(12),SUMY(8),KW,KR,AREA,TCF
3/BLK3/ETF,CPF,SI,SS,SFC,WILT,FO,FC,SMR,AVD,SNGM,TGW,TSW,TFWSN,
49K,BK,TRAIN,TMELT,TSNOW,SIO,SNIC,SMOIC,RSW,KTRL,KNTR,SMH,WHM,AVSH,
50BJ,NYR,MYR,NSW,IYR,KK,ENIC,IMJ,SMIC,CT,IX,IWS
DIMENSION XIN(6,12),XMN(12),XPM(12),DF(12),OBI(12),PL(12),PH(12),
1NL(12),PR(12)
C ** READ PATTERN SEARCH BOUNDS AND LEVELS
IF(MYR.EQ.0)GO TO 299
IF(NYR.GT.0)GO TO 310
299 READ(XR,300)NPH,NPR
300 FORMAT(2I10)
DO 309 L=1,NPR
309 READ(XR,301)L,XIN(1,L),PL(L),PH(L),NL(L)
301 FORMAT(12,17X,3(F8.0,2X),I2)
310 OBI(1)=OBJ
C ** INITIALIZE MINIMUM CONDITIONS
PRMN=OBJ
PHMN=OBJ
DO 314 L=1,NPR
XMN(L)=XIN(1,L)
XPM(L)=XIN(1,L)
PR(L)=XIN(1,L)
314 DF(L)=PH(L)-PL(L)
C * TAKE NEW PAGE WRITE PH,PL, NL
WRITE(KW,302)
302 FORMAT(1H1///10X,3HPAR,8X,2HPL,8X,2HDF,8X,2HNL///)
DO 315 L=1,NPR
315 WRITE(KW,303)L,PH(L),PL(L),DF(L),NL(L)
303 FORMAT(15X,I7,3X,3F10.3,I7)
304 FORMAT(1H1//20X,5HPHASE,I3,2X,5HPMIN=,F10.4)
305 FORMAT(5X,10F7.3)
306 FORMAT(///8X,13HIP LV PAR,10X,3H0BJ)
307 FORMAT(5X,I3,2X,I3,F11.3,5F11.4)
308 FORMAT(5X,I3,2H *,I3,F11.3,5F11.1)
C ** BEGIN PHASE LOOP
DO 309 L=1,NPH
C * TAKE NEW PAGE WRITE PHASE ONE INITIAL VECTOR
WRITE(KW,304)X,PHMN
WRITE(KW,305)(XIN(K,L),L=1,NPR)
WRITE(KW,306)
C ** BEGIN PAR LOOP
DO 309 J=1,NPR
NL0=NL(J)+1
IF(NL0.LE.2)GO TO 380
C ** BEGIN INCR LOOP
DO 370 I=1,NL0
IF(I.GT.1)GO TO 340
XNL=NL(J)
DS=DF(J)/XNL
340 XI=(I-1)
PR(J)=PL(J)+DS*XI
C * OPERATE MODEL AND DETERMINE OBJECTIVE FUNCTION
349 CALL PARSET(J,PR(J))

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SUBROUTINE PARSET(IP,PC)
C *** SET PARAMETERS TO BE OPTIMIZED
COMMON/BLK1/PRCP(12,31),TEMP(12,31),STRM(12,31),COMP(12,31)
2/BLK2/CF(12),RAD(12),MDN(12),SUMN(12),SUMY(8),KW,KR,AREA,TCF
3/BLK3/ETF,CPF,SI,SS,SFC,WILT,FO,FC,SMR,AVD,SNRM,TGW,TSW,TFWSN,
4OK,BK,TRAIN,THELT,TSNOW,SIO,SNIC,SMOIC,RSW,KTRL,KNTR,SMM,WHM,AVSM,
5OBJ,NYR,MYR,NSW,IYR,KK,ENIC,IMJ,SMIC,CT,TX,IWS
GOTO(1,2,3,4,5,6,7,8,9,10,11,12),IP
1 RK=PC
GOTO 99
2 SK=PC
GOTO 99
3 SFC=PC
GOTO 99
4 TGW=PC
GOTO 99
5 SMR=PC
GOTO 99
6 AVD=PC
GOTO 99
7 WILT=PC
GOTO 99
8 THELT=PC
GOTO 99
9 WHM=PC
GOTO 99
10 FC=PC
GOTO 99
11 SS=PC
GOTO 99
12 FO=PC
GOTO 99
99 RETURN
END

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```

CALL HYDPGV
WRITE(KW,307)J,I,PR(J),OBJ
C * IF NEW PAR. INITIALIZE LOCAL MIN
IF(I.GT.1)GO TO 367
PRMN=OBJ
XMN(J)=PR(J)
C * CHECK LOCAL AND PHASE MINS
GO TO 351
367 IF(OBJ=PRMN)350,351,351
350 PRMN=OBJ
XMN(J)=PR(J)
351 IF(OBJ=PHMN)352,370,370
352 PHMN=OBJ
DO353 L=1,NPR
353 XPM(L)=PR(L)
370 CONTINUE
C * RESET PR(J) TO FIXED LEVEL FOR NEXT PAR.
372 PR(J)=XMN(J)
CALL PARSET(J,PR(J))
CALL HYDRGY
380 CONTINUE
C ** SELECT BEST VECTOR FOR NEXT PHASE
IF(PRMN=PHMN)384,386,386
384 KFJ=K+1
DO 385 L=1,NPR
XIN(KFJ,L)=XMN(L)
PR(L)=XMN(L)
385 CALL PARSET(L,PR(L))
GO TO 386
386 KFJ=K+1
DO 387 L=1,NPR
XIN(KFJ,L)=XPM(L)
PR(L)=XPM(L)
387 CALL PARSET(L,PR(L))
388 CALL HYDRGY
OBJ(K+1)=OBJ
390 CONTINUE
C ** WRITE OUT INITIAL VECTOR TABLE
NHP=NPH+1
WRITE(KW,199)(OBJ(L),L=1,NHP)
109 FORMAT(1H1//27X,15HINITIAL VECTORS//10X,5HPHASE,7X,1H1,9X,1H2,9X,
11H3,9X,1H4,9X,1H5//12X,3H0BJ,5F10.4/)
WRITE(KW,110)
110 FORMAT(12X,3HPAR/)
NPT=NPH+1
DO91 L=1,NPR
91 WRITE(KW,111)L,(XIN(M,L),M=1,NPT)
111 FORMAT(12X,I3,5F10.3)
KK=0
CALL HYDRGY
KK=1
RETURN
END

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PAUSE 1
C ** PRCPCT PLOTTING
DO 230 M=1,IMJ
  MDAY=M*DN(M)
  CALL PENDN
DO 225 I=1,MDAY
  JJ=JJ+1
  X=FLGAT(JJ)*(.85)
  YY=PRCP(M,I)
  Y=-YY*1.27
  X=X*.25
  CALL INPLOT(X,Y)
  X=X*.85
  CALL INPLOT(X,Y)
225 CONTINUE
CALL SYMPL(1)
230 CONTINUE
CALL PENUP
X=0.
Y=-9.
CALL INPLOT(Y,Y)
JJ=1
YN=1.
CALL PLTSET(XSCALE,YSCALE,XREF,YREF,XVAL,YVAL,XP,YP,XN,YN)
CALL SVSEY
TEMP PLOTTING
DO 250 M=1,IMJ
  MDAY=M*DN(M)
  CALL PENDN
DO 255 I=1,MDAY
  JJ=JJ+1
  X=FLGAT(JJ)*.85
  YY=(TEMP(M,I)-32.)*5./9.
  Y=YY*.25
  X=X*.25
  CALL INPLOT(X,Y)
  X=X*.85
  CALL INPLOT(X,Y)
255 CONTINUE
CALL SYMPL(1)
260 CONTINUE
CALL PENUP
CALL TAPLET(X,Y)
JJ=1
YP=17.
X=1.
Y=14.9.
Z=TEMP
END

```