University of Washington
Department of Civil and Environmental Engineering

ESTIMATION OF FLOOD FREQUENCY CHANGES IN THE TOUTLE AND THE COWLITZ RIVER BASINS FOLLOWING THE ERUPTION OF MT. ST. HELENS

Dennis P. Lettenmaier
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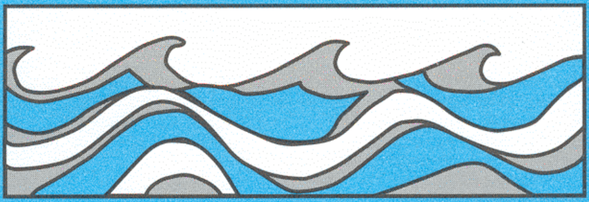

Water Resources Series
Technical Report No.69
September 1981

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ESTIMATION OF FLOOD FREQUENCY CHANGES IN THE TOUTLE AND COWLITZ RIVER BASINS FOLLOWING THE ERUPTION OF MT. ST. HELENS

by

Dennis P. Lettenmaier
and
Stephen J. Burges

Under Contract to the U.S. Geological Survey

Technical Report No. 69

September 1981

Project Completion Report:	"Cowlitz River Rainfall/Snowmelt Runoff Modeling"
Contract No.:	14-08-001-19791
Project Period:	October 1, 1980 - September 30, 1981
Principal Investigators:	Dennis P. Lettenmaier, Research Associate Professor, and Stephen J. Burges, Professor, Department of Civil Engineering, University of Washington

ABSTRACT

Changes in flood frequency in watersheds in the vicinity of Mt. St. Helens, Washington are expected as a result of changes in vegetation and alteration of land forms by the blast itself, changes in the channel system, and ash deposition. The streams most affected by the eruption are tributaries of the Cowlitz River, which, with a catchment area of nearly 3000 mi^2 at its confluence with the Columbia River, is one of the largest rivers draining the west slopes of the Cascade Mountains. To assess the effect of the initial eruption and related events, such as secondary eruptions and mud flows, on the basin, a conceptual-deterministic rainfall/snowmelt runoff model was implemented. The model was calibrated and verified for the pre-eruption conditions. Parameters were then altered to provide best and worst case assessments of post-eruption runoff response to large storms. Historic precipitation for the period 1968-1980 was routed through the model, and the predicted runoff for storms giving rise to the largest floods (four of the five largest recorded floods in the 51 year period of record occured within the study period) and selected smaller floods was analyzed. From these results, revised flood frequency curves were estimated corresponding to the two post eruption parameter sets. The estimated curves indicated that the response of the basin to moderate storms was altered much more than for large storms, for example the worst case estimates for the Toutle River are for the 5 year return period flood to increase in magnitude by approximately 37%, while the predicted increase in the 50 year flood is only about 25%. More modest change in runoff response were predicted for tributaries in the upper Cowlitz basin, where the primary impact of the eruption was deposition of volcanic ash.

ACKNOWLEDGMENTS

The work reported herein was funded by the U.S. Geological Survey, Water Resources Division, Tacoma District Office. The authors appreciate the assistance of Mr. Philip Carpenter, the project officer, in providing overall project review, and of Messrs. Ed McGavock and Rod Williams in providing hydrologic and meteorological data. John Vacarro, also of the U.S. Geological Survey, Tacoma, provided additional hydrologic and meteorological data, as well as results of hydrologic simulations using the U.S. Geological Survey catchment model for certain large flood events. The latter proved extremely useful in verifying our own simulation results for the Toutle River.

Much of the data manipulation, as well as the Cispus River modeling results, were performed by Ms. Karol Erickson, a graduate student in the Department of Civil Engineering, University of Washington. Review comments on preliminary results were provided by Professor Tom Dunne, as part of his participation in a Federal Emergency Management Agency study of flood and sedimentation hazards in the Toutle and Cowlitz River basins.

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CHAPTER I.

INTRODUCTION

The May 18 eruption of Mt. St. Helens, and subsequent secondary eruptions caused widespread devastation of the Toutle River basin, a tributary of the Cowlitz River, and lesser impacts on other tributaries of the Cowlitz River (Figure 1). Immediate effects of the eruption included flooding in the Toutle and lower Cowlitz basins resulting from rapid snow and glacier melt and debris transport, channel blockage, and movement of large quantities of sediment into the lower Cowlitz and Columbia Rivers. Reduction of channel carrying capacity and changes in the upper Toutle and Cowlitz basins raised concerns of seriously increased flood risk downstream.

Background

The U.S. Army Corps of Engineers initiated a dredging project on the lower Cowlitz River in the vicinity of the towns of Castle Rock and Longview during summer 1980 to restore the historic channel capacity of the Toutle River to the greatest extent possible. In the vicinity of Castle Rock, the community most susceptible to flooding, the target was to increase the bankful capacity of the channel to approximately 50,000 cfs. This compares with the pre-eruption bankful capacity of approximately 67,000 cfs. Additional work was undertaken upstream to attempt to prevent additional debris and sediment from reaching the lower Cowlitz by construction of debris retention impoundments

Despite these projects, even assuming no further channel reduction due to sediment transport and bank erosion, the magnitude of streamflows leading to flooding in the lower Cowlitz has been reduced. Further, there remains the question of the effect of watershed changes on flood events. The concern

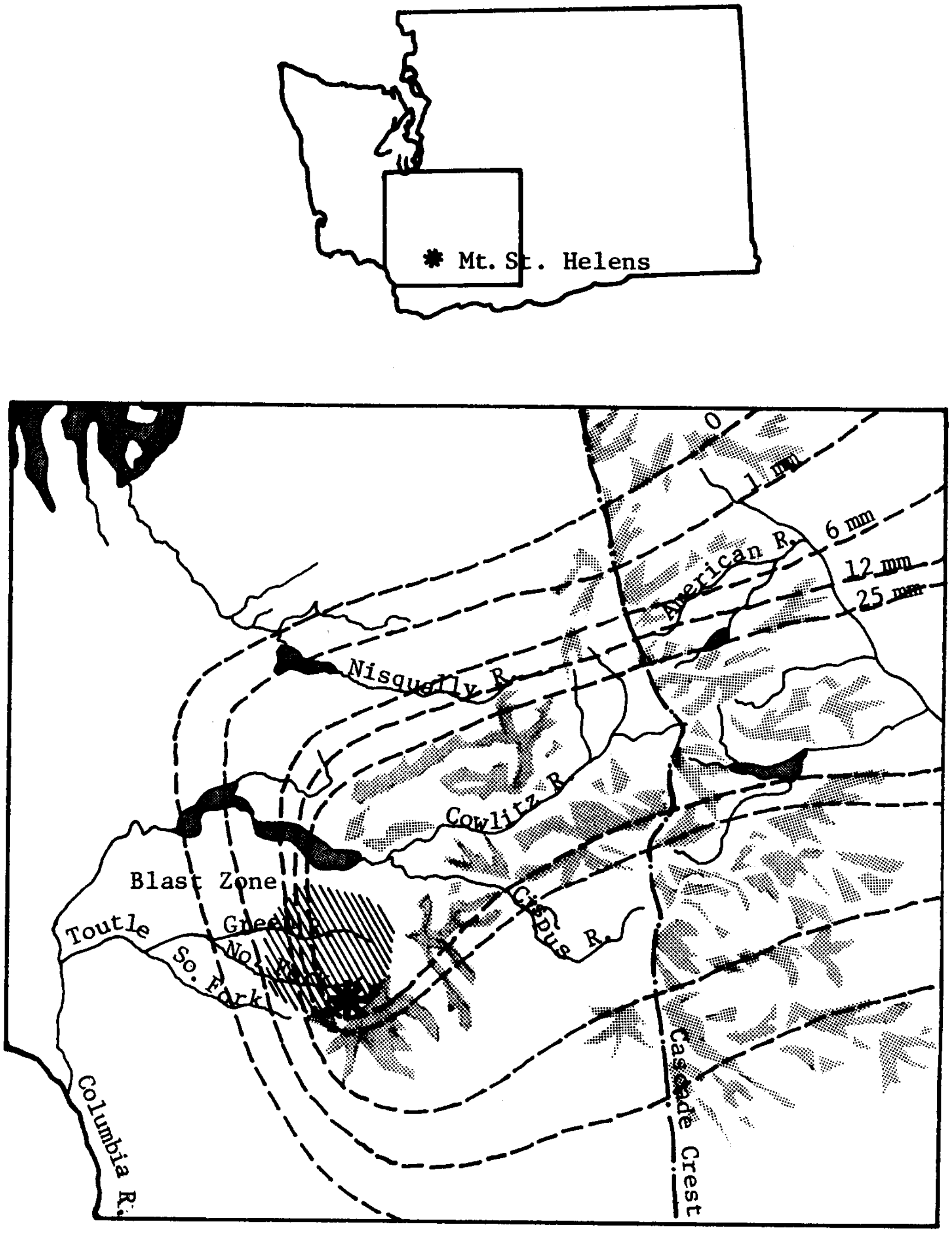


Figure 1. Cowlitz and Adjacent River Basins with Boundaries of Blast Zone and Ash Deposition Profiles from May 18 Eruption.

here is that the elimination of vegetation, reduced infiltration rates and reduction in soil moisture storage capacity in the affected areas may lead to higher runoff sustained over a shorter time period than would have occurred under historic conditions given the same rainfall events.

In recognition of the potential impact of altered rainfall-runoff response of the Cowlitz basin, the U.S. Geological Survey contracted with the Department of Civil Engineering, University of Washington, to implement a rainfall-runoff model of the Toutle River and certain subbasins of the Upper Cowlitz River. The modeling effort was to enable prediction of changes in basin response associated with recorded rainfall events that gave rise to floods. Subsequently, an effort was to be made to estimate the flood frequency distributions of these subbasins under present, post-eruption conditions. The results of this work are reported herein.

Model Selection

The model selected for the study was the National Weather Service River Forecast System, specifically the snow accumulation and ablation model of Anderson (1973) and the soil moisture accounting model of Burnash, et al. (1973). The two models were run separately, with the output of the snow model forming the input of the soil moisture accounting (runoff) model. The snow model uses a six hour time step (which is essential to allow identification of rain and snow events) while the version of the runoff model used operates on a daily time step, so snow model output is aggregated to a daily time increment. While a six hourly version of the runoff model does exist, it is not presently compatible with any University of Washington computer.

Given the constraints of data availability, particularly the deficiency of high elevation precipitation data, the daily runoff model time step was felt to give adequate resolution. Some information is included in Chapter 5 to give an idea of the relationship of annual daily flood peaks and instantaneous annual flood peaks for the basins modeled.

Since it was desired to predict the impact of watershed changes on runoff, it was necessary to split the basins (Figure 1) into subbasins, for which projected physical impacts could be estimated. Unfortunately, the gaged basins, typically of area on the order of 500 mi^2, were too large to serve this purpose directly. The usual approach in simulation of mountain watersheds is to divide the gaged basins into several elevation zones. The snow model is then applied to each elevation zone, and the output treated as a single precipitation record. The precipitation records are then weighted to form a 'mean areal precipitation' record, which is the single input to the runoff model. Use of elevation zones is essential in areas such as the Northwest where low elevations usually receive rain and higher elevations snow from the same storms.

Modeling Approach

In this work, a somewhat different approach from the mean areal precipitation method was used in modeling the Toutle River. Rather than weighting the output of the snow model from each elevation zone to provide a single input for the runoff model, the runoff model was driven separately with each snow model output record. A weighted average of the predicted runoff from each elevation zone, with weights that were proportionate to the area of each zone, was used as the predicted basin runoff. This method, although complicating the calibration procedure, retains the flexibility to alter parameters which should be changed to reflect eruption effects independently for each zone, rather than attempting to assign average parameters for the entire basin.

This is especially important in the case of the Toutle River, where the watershed was only minimally impacted at low elevation, but where major changes including elimination of forest cover and deposition of large amounts of blast material and ash occurred at the higher elevations. The Cispus River modeling effort was hampered by the absence of adequate meteorological stations, and in view of the much less severe effects of the eruption on this basin. The simpler mean areal precipitation approach was used.

Initially, it had been hoped that the model could be recalibrated for the post-eruption period, i.e., that the runoff data could be used to infer changes in the model parameters. However, the occurrence of the eruption in the late spring and the necessity to complete the work during Fall 1980 (preliminary estimates of flood hazard for the Toutle River were provided in mid-November, 1980) afforded little chance for recalibration, since most of the runoff in the May-November period was characterized by a recession from the previous winter basin moisture storage, with few major storm events. Although recalibration may be possible following the winter, 1981 runoff season, the approach used here was to review conditions within the basin, then to alter model parameters for the various elevation zones to reflect both a 'worst case' scenario, i.e., the most severe alteration of watershed conditions which might reasonably have occurred, and a 'best estimate', reflecting the judgment of the investigators as to the set of model parameters which is most likely to reflect present, post-eruption conditions. The model was subsequently rerun using recorded precipitation and temperature data for water years 1968-80, and estimates of changes in the largest flood events were observed. Conveniently, four of the five largest annual floods of the 51 year record for the Toutle River occurred during the 1968-80 period. Analysis of these peak floods along with several smaller events which were well-simulated in the initial calibration and verification runs allowed estimates to be made of the flood frequency distribution under current conditions.

In the remainder of this report, details of the simulation methodology, including description of the basin and available data (Chapter II, selection of meteorological stations used in the simulations and model implementation (Chapter III), model calibration and verification results (Chapter IV), and discussion of recorded and projected basin response for annual flood events (Chapter V) are given. Chapter VI summarizes and concludes the work, including a discussion of likely causes of error in the simulation, with implications for future additional data stations, and the judgement of the authors as to the viability of deterministic modeling in watersheds with limited data.

CHAPTER II.

BASIN DESCRIPTION AND DATA AVAILABILITY

Basin Description

Figure 1 (Chapter I) shows the Cowlitz/Toutle River drainage basins with respect to Mt. St. Helens, and the areas of major impact. Figure 2 shows the hydrometeorological stations in the vicinity of the two basins. The U.S. Geological Survey maintains several stream gaging stations in these basins, generally at the mouth of major tributaries. Our major emphasis in this study was on the Toutle River, the most impacted drainage. Therefore the key stream gaging station is USGS #14-2425, near Silver Lake. This gage records flow from approximately 474 mi^2 of the approximately 512 mi^2 of the Toutle River drainage at its confluence with the Cowlitz. Although this gage was destroyed in the mud flows following the May 18 eruption (and subsequently restored several months later), our approach makes use exclusively of pre-eruption hydrometeorological data, so the post eruption data base is not of direct concern. Likewise, although additional gaging stations were installed on several tributaries of the Toutle following the eruption, these stations were not used in the analysis.

In the interest of predicting runoff effects from a drainage impacted primarily by ash deposition, rather than direct blast effects, the Cispus River basin, adjoining the Toutle to the North and East, was also modeled. As shown in Figure 2, this area, primarily the upper reaches of the basin, was heavily impacted by ashfall, however it was outside the area affected directly by the blast. The gaging station used in this basin was USGS #14-2325, near Randle, with a drainage area of 321 mi^2.

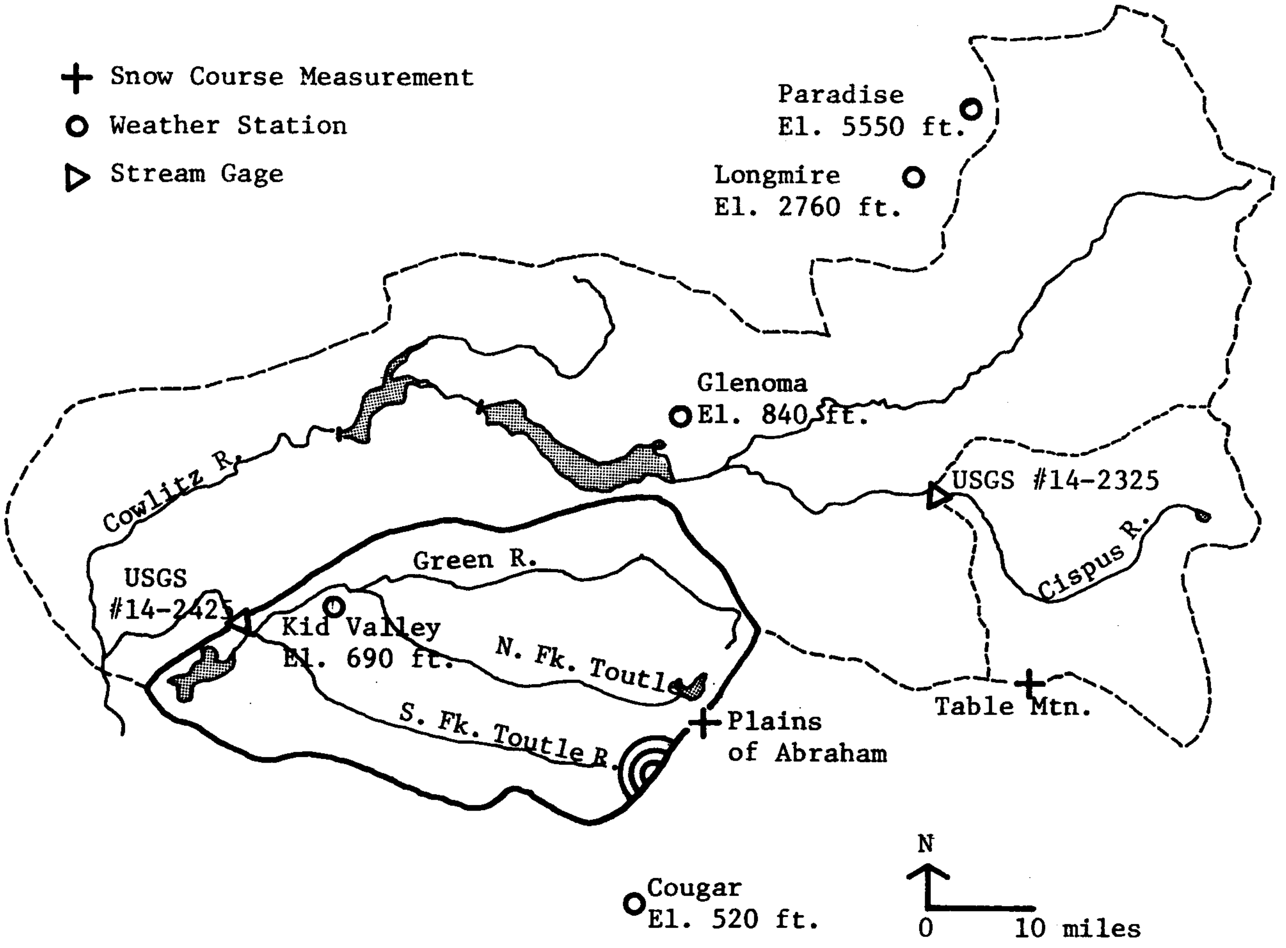


Figure 2. Cowlitz and Toutle River Basins with Key Stream Gage, Meteorological and Snow Course Stations.

Table 1 shows pre-eruption characteristics of the two drainage basins. Both have small glacierized areas, constituting less than 1% of the respective total drainage areas. In the case of the Toutle, the glacierized area, much of which was removed by the May 18 eruption, is on Mt. St. Helens. The glacierized area in the Cispus River is on Mt. Adams, which at over 12,000 ft is the highest point in the basin. It should be emphasized, especially in the case of the Toutle, that the basin characteristics given are pre-eruption, baseline conditions.

Table 1. Pre-Eruption Basin Characteristics for Toutle and Cispus River Basins (from U.S. Geological Survey Basin Characteristics File)

	Toutle River (above USGS #14-2425)	Cispus River (above USGS #14-2325)
Drainage area, mi^2	474	321
Mean basin elevation, ft.	2,310	4,130
Mean annual precipitation, inches	84	84
Mean channel slope, ft/mile	78	84
Stream length, miles	44	38
Forested area, per cent	94	76

Previous experience (e.g., Kitanidis and Bras, 1980) has shown that precipitation input errors are often the most important source of runoff simulation error. Therefore, selection of precipitation stations is a critical concern in the modeling process. The problem is expecially difficult in mountainous areas, where there is often a paucity of meteorological stations. Figure 2 shows that the Cowlitz/Toutle basins are no exception, with most gaging stations located at low elevations. (Although several additional stations exist, we have shown only those with sufficient record length and quality of record to be suitable for continuous simulation.) Only one of the gages is located within the Toutle River drainage, and none are in the Cispus drainage.

One critical aspect of simulating rainfall/snowmelt/runoff dynamics in mountainous regions is proper establishment of the precipitation-elevation relationship. Orographic effects, which predominate throughout most of the year in these basins, dictate that precipitation will generally increase with elevation; estimation of the rate of increase is difficult especially when many of the stations lie at low elevation, and when the high elevation stations are susceptible to substantial catch deficiency. Figure 3 shows mean

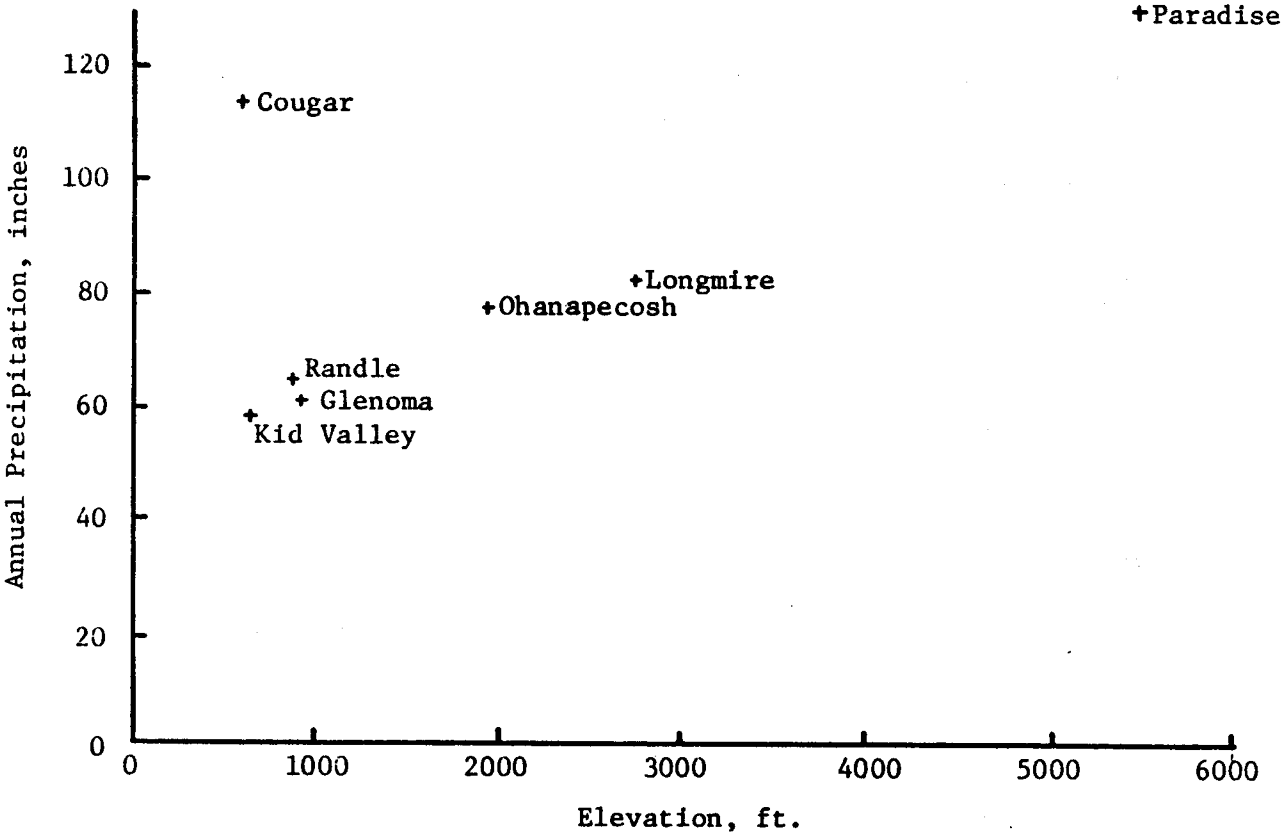


Figure 3. Mean Annual Precipitation vs. Elevation for Six Stations in Vicinity of Cowlitz River Basin.

annual precipitation for the seven stations shown in Figure 2. With the exception of Cougar, the relationship appears to be nearly linear, however the very high precipitation and low elevation of Cougar suggest that this apparent linearity is an aberration caused by fortuitous location of the remaining six stations. This conclusion was born out in early simulation runs, which suggested that the rate of change of precipitation with elevation must be higher than that indicated by the stations plotted, and particularly in the case of the Toutle, that the relationship is nonlinear. For these reasons, and adaptive approach to defining precipitation-elevation relationships, described in Chapter 3, was adopted.

Temperature relationships are shown in Figures 4 and 5. Generally, temperature shows much less areal variability than does precipitation, and the clustering of the Kid Valley, Glenoma, and Cougar stations confirms this. The lapse rate (rate of temperature decrease with elevation) is nonlinear, with an average annual rate of about 2.5°F/1000 ft below Longmire (elev. 2760 ft), and about 3.6°F/1000 ft above Longmire. Figure 5, however, shows that the nonlinearity is highly seasonal, during the months with highest precipitation (December-March) the lapse rate is nearly linear which would be expected from meteorological considerations. For the purposes of modeling snowmelt, the lapse rate is of greatest importance during the winter months, and as such a linear rate, assumed by the model, was considered justified.

Elevation Zone Partitioning

As described in Chapter I, the rainfall-runoff model was structured to accept snowmelt and rainfall estimates from each of several elevation zones. In the case of the Toutle, four elevation zones were used, while for the Cispus, which is generally more remote from the available precipitation gages, two elevation zones were used.

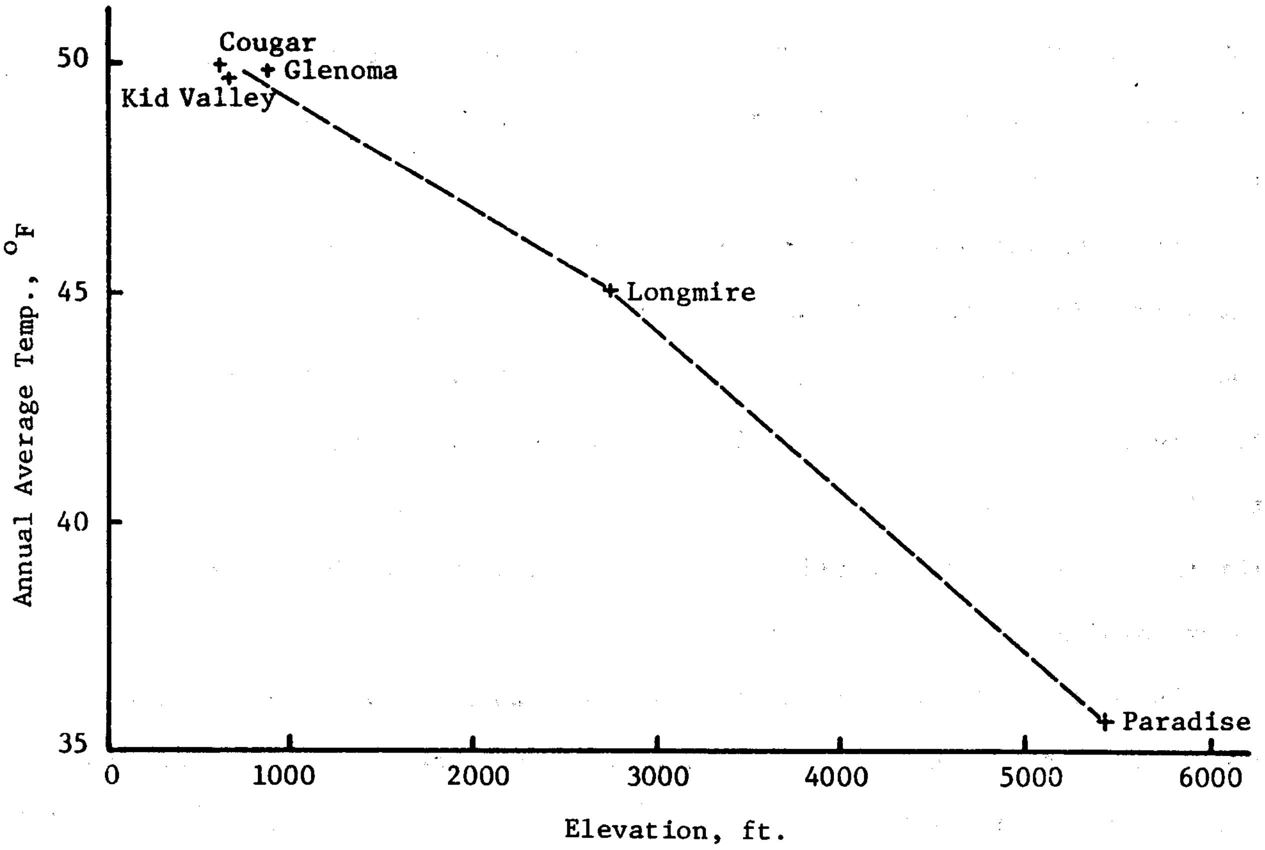


Figure 4. Mean Annual Temperature vs. Elevation for Five Stations in Vicinity of Cowlitz River Basin.

The elevation ranges of the zones (Table 2) were selected through use of hypsometric curves for each basin (Figures 5a and 5b), with the zones selected to assure roughly equal area fractions in each zone consistent with the elevation of meteorological stations and observations of the fraction of precipitation occurring as snow at various elevations. For instance, Toutle River Zone 3 was selected to have median elevation approximately equal to that of Longmire, so that the Longmire temperature record could be used directly for this zone.

For each elevation zone, one precipitation gage was assumed to characterize best the average precipitation in that zone. Table 3 below shows the stations selected for each zone. The selection was based on physical

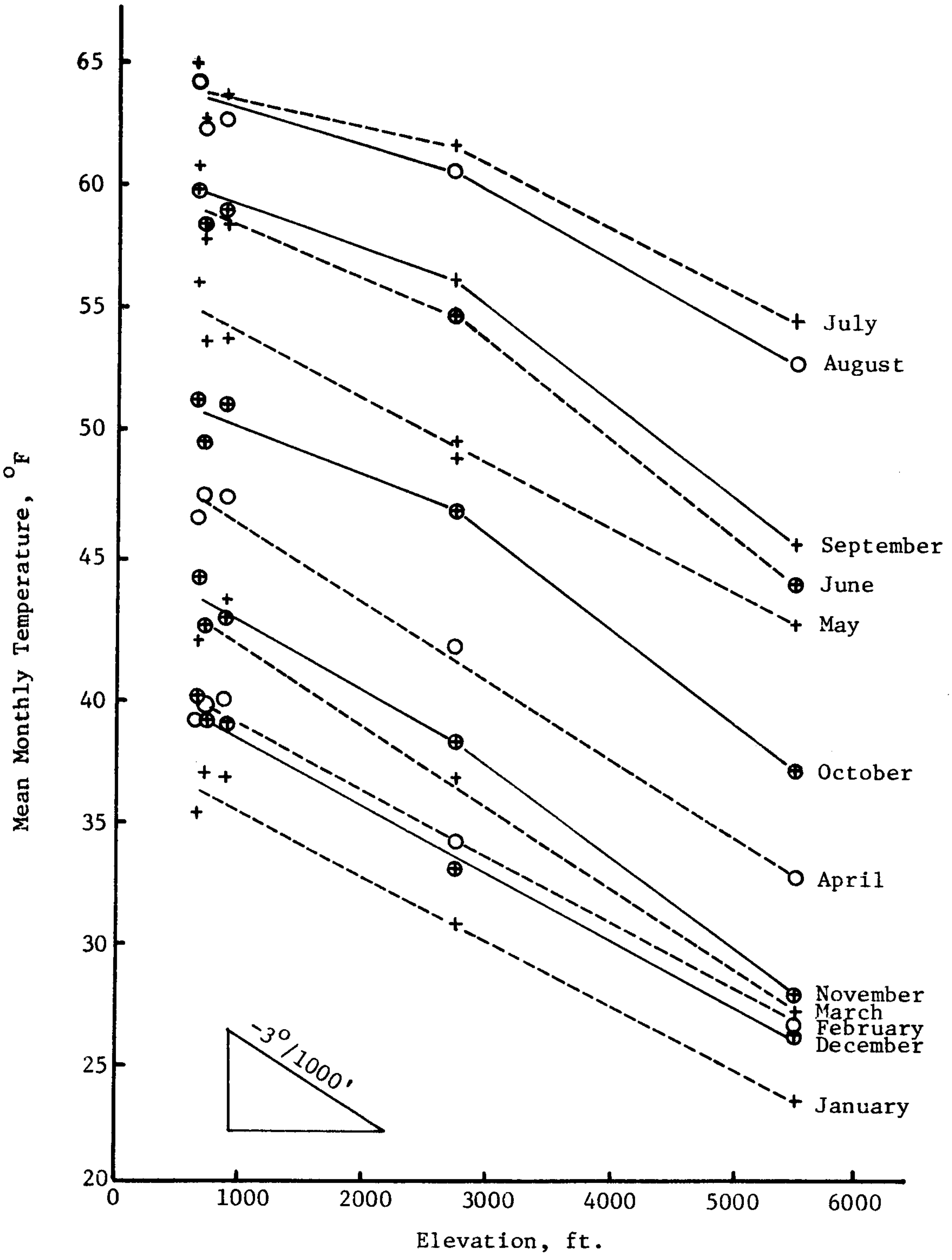


Figure 5. Mean Monthly Temperature vs. Elevation for Five Stations in Vicinity of Cowlitz River Basin.

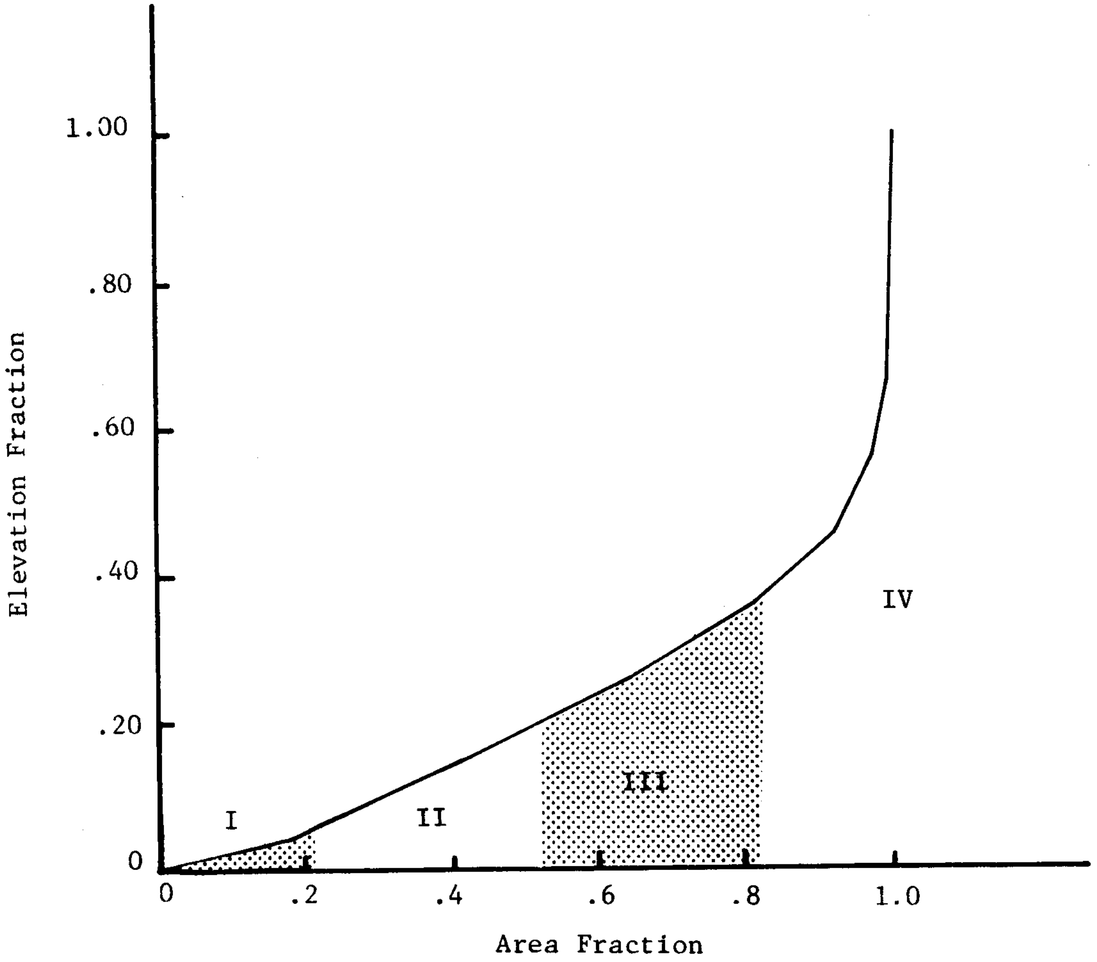


Figure 5a. Normalized Hypsometric curve for Toutle River Basin with Elevation Zones.

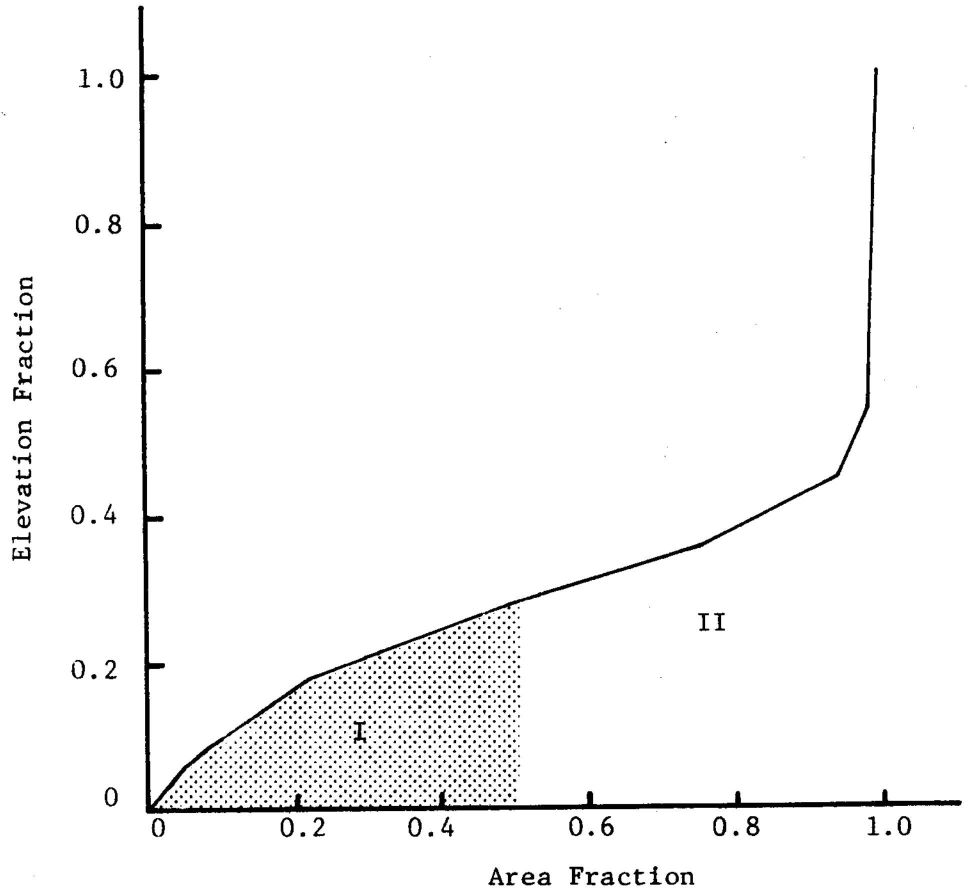


Figure 5b. Normalized Hypsometric Curve for Cispus River Basin with Elevation Zones.

Table 2. Elevation Zones for Toutle and Cispus River Basins

Zone	Toutle River Elevation Range, ft	Toutle River Med. Elev., ft	Toutle River % Basin Area	Cispus River Elevation Range, ft	Cispus River Med. Elev., ft	Cispus River % Basin Area
1	400-1000	700	22	1220-4000	3300	50
2	1000-2000	1500	30	4000-12,300	4650	50
3	2000-3500	2700	30			
4	3500-	4100	18			

Table 3. Precipitation and Temperature Gages Representing Various Elevation Zones

Zone	Toutle Precipitation	Toutle Temperature	Cispus Precipitation	Cispus Temperature
1	Kid Valley	Kid Valley	Kid Valley	Kid Valley - 3.4°C
2	Glenoma	Longmire-Paradise (interpolation)	Longmire	Longmire - 2.6°C
3	Cougar	Longmire + 0.5°C		
4	Cougar	Paradise + 2.0°C		

proximity of the stations, as well as other considerations which might influence representability of a station (for instance, Cougar, although a low elevation station, was felt by virtue of its high precipitation and proximity to the high elevation zones in the Toutle to be more representative of high elevation conditions). Finally, it should be noted that the raw station records were scaled (constant multiplier) to estimate areal precipitation appropriate to each elevation zone, as described in Chapter 3.

Snow Course Selection

Figure 2 also shows snow courses in the Soil Conservation Service cooperative system located in the vicinity of the Toutle and Cowlitz basins. These stations ideally could be used to calibrate the predicted snow water equivalent for each elevation zone in the manner described by Parkinson (1979). It was found, however, that the observed snow water equivalents often did not characterize elevation zone mean conditions, as predicted by the model, hence these records were of minimal use for calibration of the model. The data did serve a more limited purpose in assuring that the model was properly predicting the initiation of snow accumulation in the Fall and the final removal of the snowpack in the Spring or summer. The snow courses most useful for this purpose were the Plains of Abraham (SCS 22C1) for the Toutle and Table Mountain (SCS 21C24) for the Cispus.

CHAPTER III.

MODEL IMPLEMENTATION

Model implementation consists primarily of manipulation of input data into a suitable form to drive the model. For the snowmelt/rainfall-runoff models used, input data are six hourly precipitation and temperature. In addition, daily runoff data are used in the model for calibration.

Input Data Processing

Handling of runoff data was straightforward, as these are retrievalbe from the USGS WATSTORE automated data handling system in standard, 80 column card image format. A minor modification was made to the NWS runoff model to allow files structured in the USGS format to be read directly. No missing data were encountered for either streamflow record used. Water years 1968-80 were used for both basins.

Precipitation and temperature data preparation proved a more cumbersome logistical exercise. These data were acquired in magnetic tape form from the National Environmental Data Center, Asheville, N.C. in what is termed the Office of Hydrology format. This format, designed for compatibility with the NWS River Forecast System models, consists of 960 character record lengths with an entire month's meteorological data on each record. Although a number of parameters are provided, only daily precipitation and temperature maxima and minima were required. The initial step in the process was to transcribe the data to 80 column card image formats (4 card images per month) with separate files for precipitation, temperature maxima, and temperature minima. Subsequently, these files were searched for missing or mis-recorded data. The latter occured occasionally in precipitation volumes when the daily precipitation is not recorded and is combined with the following day's volume. Estimates of missing precipitation data were made by applying the ratio of the monthly average precipitation at the station with missing data (primary) to the monthly average at a nearby (secondary) station to the secondary site observation. Missing temperature data were estimated by applying the deviation of recorded temperature from the monthly average at the secondary site to the primary site.

This process resulted in three files for each of the six meterological stations shown in Figure 2, with the exception of Ohanapecosh, where no temperature records are kept. Ultimately, this station was dropped and only the remaining five were used as indicated in Table 2.

Precipitation and Temperature Disaggregation

The final process in the data manipulation stage was to estimate six hourly rainfall and temperature data as required for the snowmelt model. Insofar as none of the five stations used have records at less than a 24-hour increment, a process of disaggregation was necessary. A review of our existing library of hourly precipitation data for Washington indicated the only station at which a high quality (minimal missing data) record exists in Southwest Washington is at Olympia, approximately 55 mi. NNW of the Toutle basin centroid, and approximately 75 mi. NW of the Cispus basin centroid. Although this station is more remote from the basin than we would prefer, most winter storms in the Toutle and Cispus basins result from Pacific frontal activity of large areal extent, so at least for the storms with greatest intensity our method is defensible. Perhaps more importantly, some limited sensitivity analysis indicated that, generally, predicted runoff was not highly sensitive to the method of disaggregation. This is so because the runoff model accepts daily rain on bare ground plus snowmelt, which is the aggregated total of the six hourly predications. Thus, the disaggregation method is irrelevant when no snow is present, and when snow is present it matters only when the precipitation occurs partly as snow and partly as rain. Further, with multiple elevation zones the rain/snow distribution is often important for only one zone.

Temperature maxima and minima were disaggregated to a six hour time base through use of the following equation, recommended by the National Westher Service (Anderson, 1973):

$$\underline{T} = A\underline{T}^*$$

where $\underline{T} = (T_n \; T_m \; T_a \; T_e)'$; $\begin{aligned} n &= 0000\text{-}0600 \\ m &= 0600\text{-}1200 \\ a &= 1200\text{-}1800 \\ e &= 1800\text{-}2400 \end{aligned}$

$$\underline{T}^* = (MX^- \; MN \; MX \; MN+)';$$

MX^- = previous days' maximum temperature
MN = present days' minimum temperature
MX = present days' maximum temperature
MN+ = next days' minimum temperature

and the coefficient matrix is

$$A = \begin{bmatrix} 0.05 & 0.95 & 0 & 0 \\ 0 & 0.40 & 0.60 & 0 \\ 0 & 0.025 & 0.925 & 0.05 \\ 0 & 0 & 0.33 & 0.67 \end{bmatrix}$$

when the temperature vectors $\underline{T}$ and $\underline{T}^*$ are in degrees F.

Elevation Adjustment of Temperature and Precipitation

Following disaggregation of the raw meteorological records to a six hour time base, adjustments were made to provide representative records for each elevation zone. This was achieved by selecting a station whose physical characteristics (elevation and geographic coordinates) where thought to be representative of the zone, as discussed in Chapter II. Subsequently, temperature records were adjusted to elevation zone mean elevation using a constant lapse rate. Precipitation records were all scaled to have an annual mean equal to an arbitrary base, approximately equal to the zone I mean. Precipitation records for all other elevation zones were subsequently scaled by a factor equal to one plus a constant times the difference between the mean elevation of the zone in question and zone I. This linear precipitation-elevation relationship was used as an initial approximation, with the constant a model calibration parameter. The relationship could also be changed by adjustment of the precipitation factor in the snowmelt model, however this factor was originally set to 1.0 in the interest of minimizing the number of calibration parameters.

Because both the snowmelt and runoff models were run for each zone, it was necessary to add the predicted runoff for each zone to obtain predicted basin runoff. This additional step, not necessary when the mean areal precipitation approach is used, required a minor adjustment to the graphical display package included with the runoff model. The modification allowed runoff contributions from each of the elevation zones, in addition to total predicted basin runoff, to be compared with recorded runoff. This display was extremely useful in infering errors in winter runoff predictions caused by misidentification of rain and snow events, typically of interest in upper zone runoff.

Once the model had been implemented, the normal calibration process, consisting of trial and error adjustment of model parameters and precipitation and temperature factors, was followed. This process is described in detail in Chapter IV, with emphasis on the Toutle River basin.

CHAPTER IV.

MODEL CALIBRATION AND VERIFICATION

In Chapters I-III, we have described the problem of estimating flood frequency changes in the Cowlitz and Toutle basins, identified available data records suitable for continuous hydrologic simulation, and described the process of manipulating these records into a form suitable for continuous simulation in watersheds with large variations in elevation. Although the choice of models (the NWS River Forecast System) has been indicated, no discussion of the particulars of these models has been provided, and it seems appropriate to include a brief description here. Following this, specific results of calibration and verification runs with emphasis on the Toutle River, are given.

Snow Ablation and Accumulation Model

Much research has been done on the physics of snow ablation and accumulation at a point. Extensive instrumentation is necessary to measure the dominant variables in the heat and moisture exchange processes at a point. While modeling point processes is difficult, integrating the state of the snowpack over a catchment, an approach based on point estimates, is essentially hopeless, given the large areal variability of many of the subprocesses. Anderson (1973) proposed a model that uses temperature indices of the dominant melt and accumulation processes. His approach has the advantage of avoiding the necessity for collection of extensive radiation data. The Anderson model requires: areal average six hour precipitation totals; daily maximum and minimum temperatures, index temperature (to determine if precipitation is rain or snow); and specification of a (constant) lapse rate for adjustment of temperature with elevation. The dominant model features are given in Anderson's Table 3.1 and Figure 3.1, shown here as Table 4 and Figure 6, respectively. Complete details of the model are given in Anderson (1973).

Streamflow Simulation Model

The first effective simulation models that provided detailed information about hydrograph shape, resulting from a particular storm on a catchment, used some form of an antecedent precipitation index to permit estimation of the precipitation excess, and an appropriate unit hydrograph. This was an effective method for forecasting river stages for major storms. The unit hydrograph combined the effects of the land surface and the channel system. The method assumes that the basin behaves linearly; it is well known, however, that nonlinear flow dynamics are important (see, e.g., Linsley, et al., 1975).

Limitations in simulating catchment response to individual storms led to development of continuous simulation models where a moisture budget is maintained continuously (typically for time increment of one, six, or twenty-four hours) for the catchment. Most continuous simulation models have the same basic features: they have a moisture accounting scheme for moisture stored on the land surface and in the soil, and for water traveling through the space or over the land surface; they also have a method for routing water supplied to the channels through the channel system. The differences between models depend on how the land processes are modeled and how the channel flow routing is effected. Most of these models are conceptual in that different land processes are represented as releases of water from conceptual storages. This means that few directly measurable catchment soil characteristics can be incorporated directly into the models.

Table 4. Snow-Air Interface Heat Exchange Summary (Table 3.1 From Anderson, 1973)

A. AIR TEMPERATURE > 32°F

1. No rain or light rain (<0.1"/6 hr)

Heat Exchange = $(T_a - \text{MBASE})$ Melt factor

2. Rain ($\geq$0.1"/6hr)

Assume: no solar radiation

longwave equals blackbody radiation at air temperature

dew-point = air temperature

temp. or rain = air temperature

$$\text{Heat exchange} = 0.007 \cdot (T_a - 32) + 7.5 \cdot \lambda \cdot f(\mu) \cdot (T_a - 32) + 8.5 \cdot f(\mu) \cdot (e_a - 0.18) + 0.007 \cdot \text{Rain} \cdot (T_a - 32)$$

γ = psychrometric constant, e_a = vapor pressure

$f(\mu)$ = wind function

B. AIR TEMPERATURE $\leq$ 32°F

Heat Exchange = $(T_{a_2} - ATI_1) \cdot$ Negative melt factor

ATI is antecedent temperature index

$ATI_2 = ATI_1 + TIPM \cdot (T_{a_2} - ATI_1)$

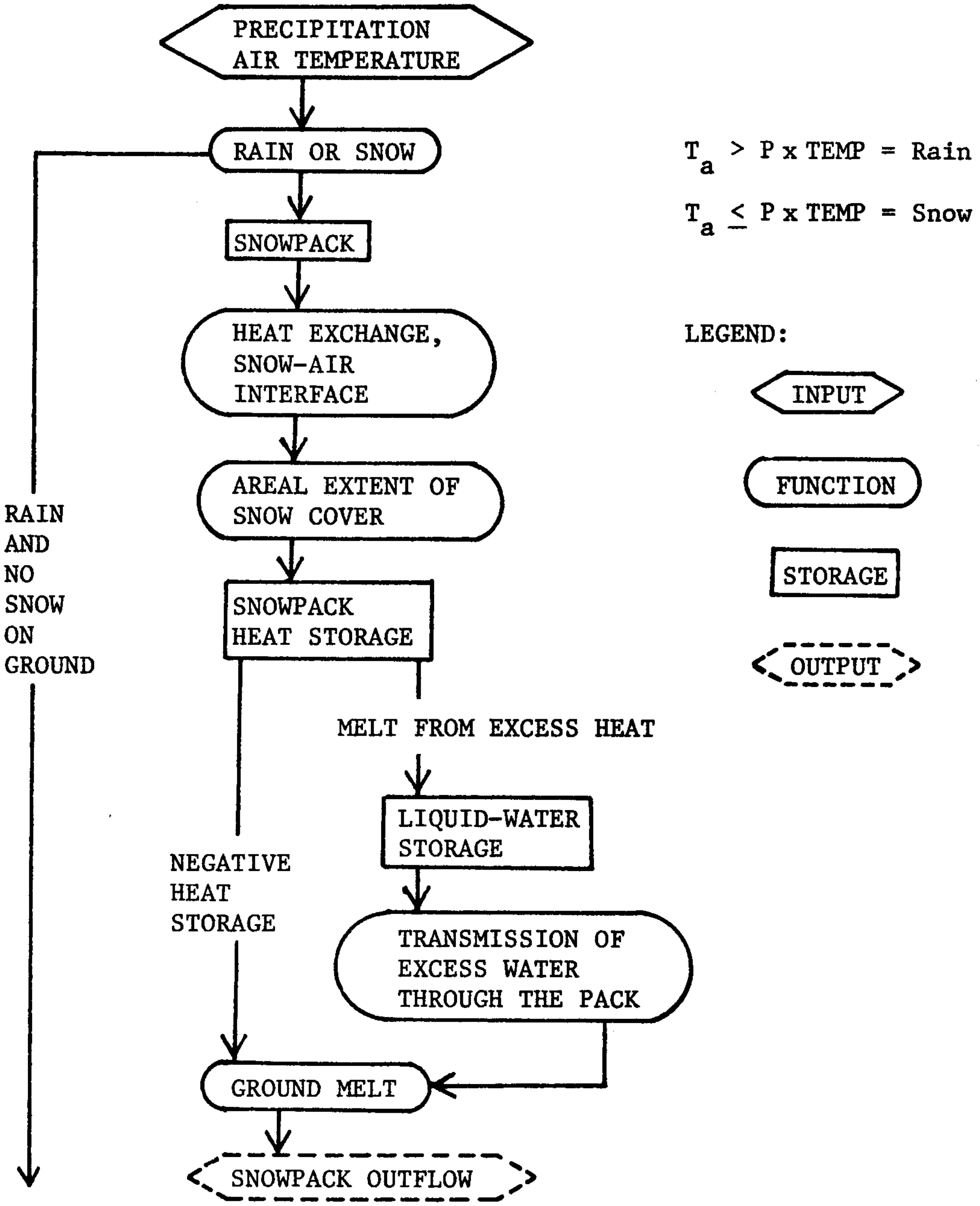


Figure 6. Flow Chart of National Weather Service Snow Accumulation and Ablation Model (Figure 3.1 from Anderson, 1973).

We chose the Sacramento Model (Burnash, et al., 1973) because its lumped representation of catchment features was consistent with data availability for this project. Other continuous simulation models would probably have been satisfactory; however the way in which soil moisture is modeled in the Sacramento model is more sophisticated than many others, and this influenced our decision. It should be noted that the National Weather Service has adopted the Sacramento model as the soil moisture model in its River Forecast System, so the two terms are interchangeable.

The Sacramento model structure, described in Burnash, et al. (1973), is schematized in Peck (1976). The relevant figures from this publication are reporduced here as Figures 7 and 8, respectively. All the variables in Figure 8 are given in Appendix A. The model is calibrated for a given catchment as follows. First, continuous precipitation and streamflow files are set up for the period of interest; the calibration period is typically five or six years of record that contain extreme wet and dry conditions, if possible. Next, initial estimates of all the conceptual storages, reservoir decay coefficients, etc., are made. These quantities are referred to as parameters and are changed as needed during calibration.

The model is then operated using the precipitation input to simulate streamflow at the gage of interest. Simulated streamflow is compared with recorded streamflow, and model parameters adjusted and the model rerun until recorded and simulated streamflow are in close agreement. There is an optimization procedure that may be used to adjust parameters, however we have found it to be quite expensive and sometimes unreliable, so we elected to use manual calibration.

The above procedure is used when the catchment is modeled as a single contributing area. Clearly, where orographic effects are experienced and/or

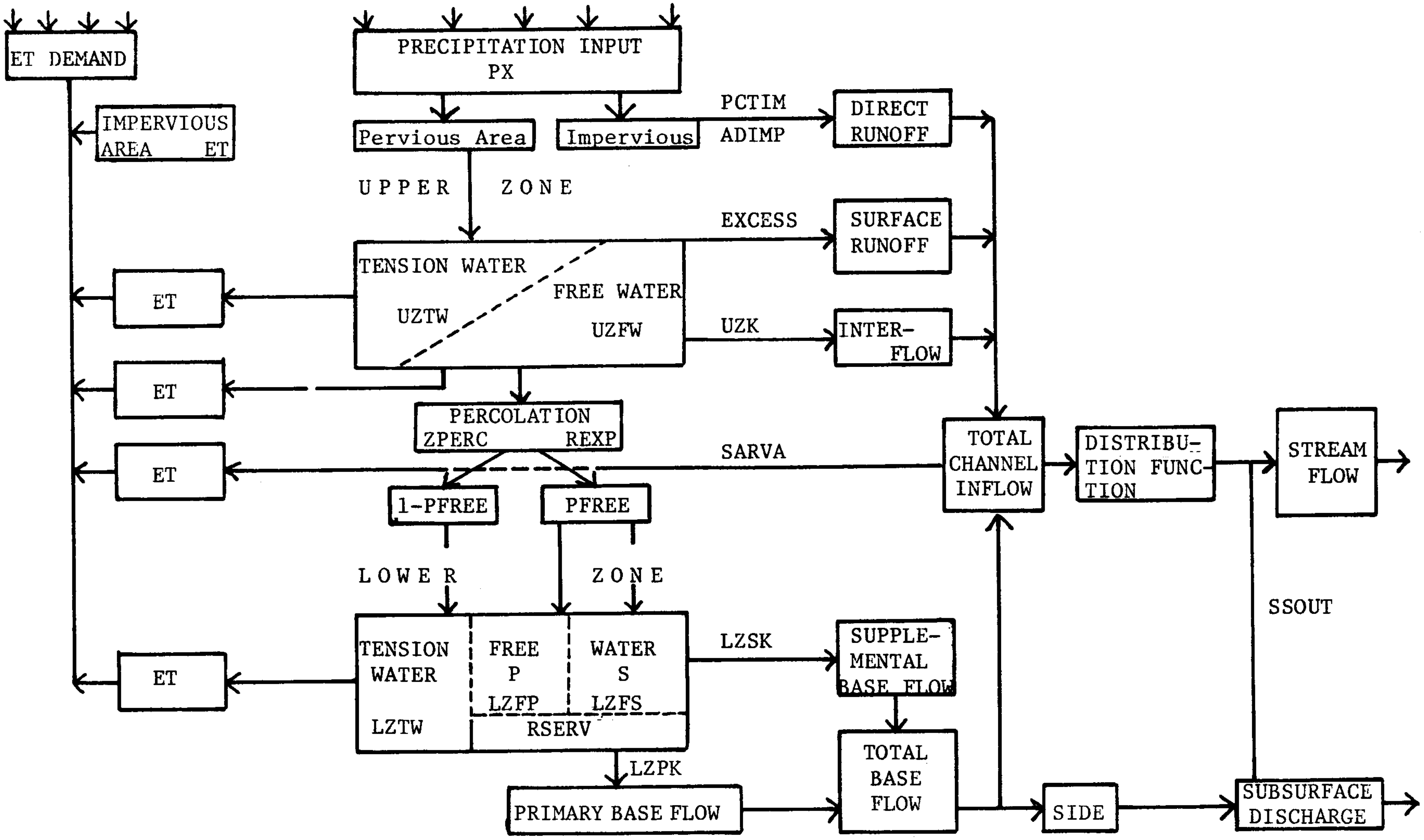


Figure 7. Schematic of National Weather Service River Forecast System Catchment Model - Sacramento Model (Fig. 1 from Peck, 1976).

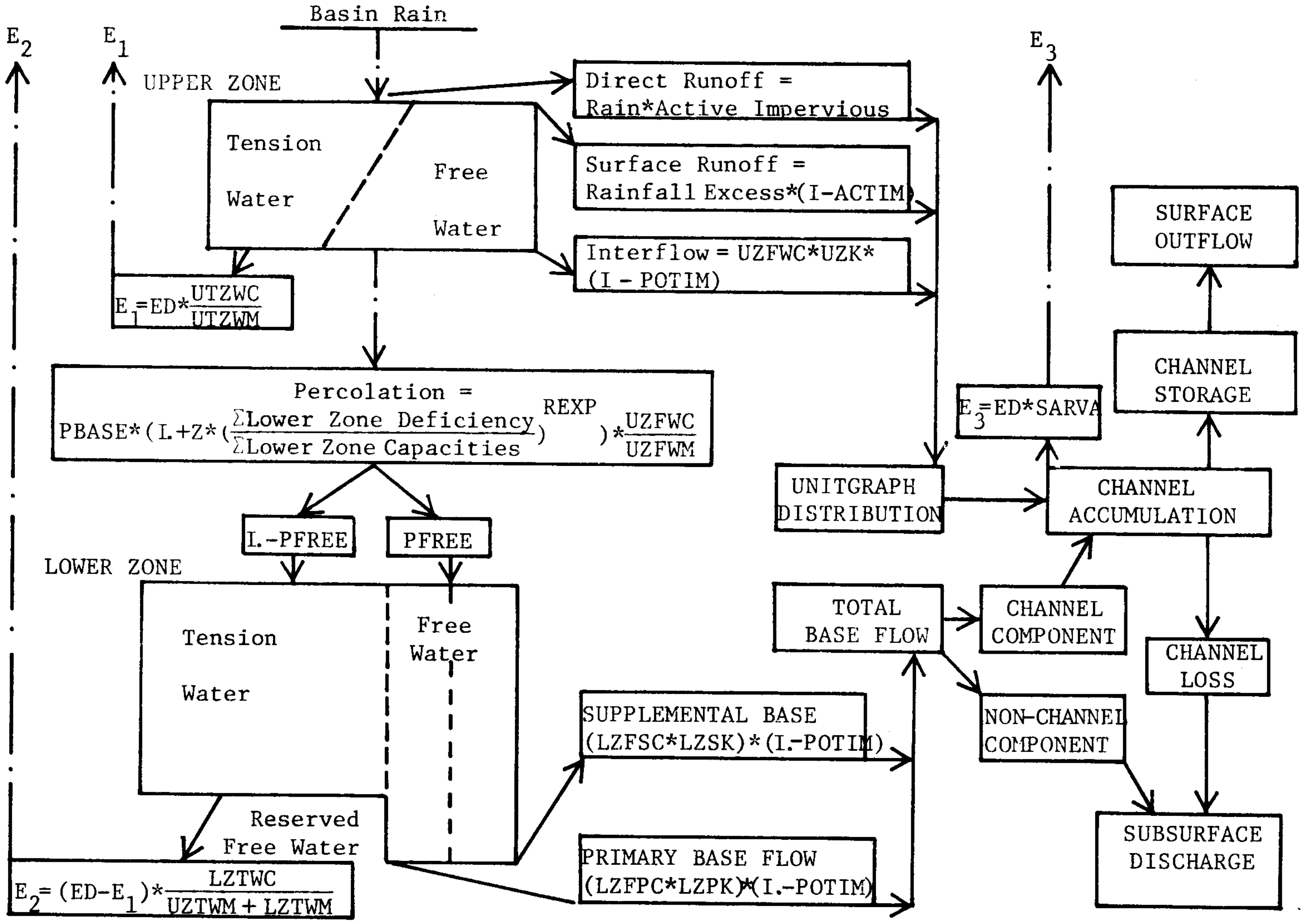


Figure 8. Functional Relationships Used in the Sacramento Model.

more than one precipitation station is available, the catchment should be modeled as several subareas. The basins involved were divided into several elevation zones, as described in Chapter 2; these zones may be effectively considered to be subbasins.

Before giving additional details of use of the model it is appropriate to examine the major components of Figure 8. The land component is broken into pervious and impervious fractions. Rain falling on the impervious fraction becomes, after extraction for interception and depression storage, direct surface runoff. The pervious fraction (most of Figure 8) is modeled as two conceptual storages, an upper zone and a lower zone. The upper zone is divided into two components: tension water, that can only be drained by exfiltration processes; and free water that supplies interflow and the lower zone storage. The upper zone represents interception, depression and upper soil moisture storage and is extremely influential on short term catchment response to precipitation. The lower zone contains a tension water zone (water can be removed only via exfiltration) and two (primary and supplemental) free water zones that supply base flow. The primary and supplemental zones are used to model variable baseflow decay rates, and in effect model baseflow recession as a nonlinear reservoir.

The two components of direct interest for modeling changed hydrologic response in the vicinity of Mt. St. Helens are impervious area and upper zone storage. Field observations made available to us by the U.S.G.S. indicated that in regions covered by mud blast deposits, ash, or pyroclastic flows, the surface is virtually impermeable; the land surface is highly erosive so overland flow distances are very small before first order channels form. From the standpoint of rainfall response, however, there is little difference between drainage from an impervious surface and from a permeable surface covered with very small channels. Where vegetation has been removed, as in the blast zones, the upper and lower tension water zones are smaller; the overall size of the upper zone storage increases because of the increased depression storage (debris, etc.).

While changed land surface characteristics also give rise to changed snowpack features, we did not modify the psuedo precipitation predictions yielded by the Snow Ablation and Accumulation Model, since our principal interest lay in predicting flood response. Historically major floods have occured in December and January when the land is saturated and storm mechanisms remove relatively newly deposited snow. The changed land surface and effects of vegetation removal, on the other hand, are more important to snow modeling later in the season, when substantial changes in the amount of snow accumulation, and therefore its ablation characteristics, may be expected.

Model Calibration, Toutle River

Our major emphasis was modeling flood response in the Toutle catchment above USGS gauge 14-2425, near the mouth of the Toutle River. Therefore, complete details concerning model calibration are given for that catchment. A much shorter summary is given for the upper Cowlitz basin modeling.

The precipitation and temperature data files have been summarized in Tables 2 and 3 (Chapter II). Precipitation adjustment factors are given in Table 5. Four subcatchments were used corresponding to the four elevation zones. The various multipliers were used to obtain an approximate orographic relationship. These multipliers represent an adjustment of the initial linear relationship described in Chapter III. It should be noted that the Kid Valley station was the only station in the catchment, albeit at low elevation.

The plausibility of the weighting factors given in Table 5 determined by how well the snowpack in each zone agreed with the available snow course data. As discussed in Chapter II, snow course data were extremely limited so direct calibration of the snow model was only approximate.

Table 5. Precipitation Station Multipliers, Toutle River Basin.

Zone	Mean Elevation (feet)	Precipitation Station	Multiplier[(a)]
1	700	Kid Valley	1.0
2	1500	Glenoma	1.37
3	2700	Cougar	1.41
4	4100	Cougar	1.56

[(a)] multiplier for normalized station record with annual mean precipitation adjusted to Kid Valley (see Chapter II)

The data records summarized in Table 5 were used separately with the streamflow simulation model; simulated flows from each zone were added to yield total simulated flow at gauge No. 14-2425. Precipitation weights were applied to each of the zonal psuedo precipitation records to ensure that a satisfactory water budget was maintained. Final values for each zonal precipitation weighting factor are given in Table 6. Also given in Table 6 are the land surface parameters for the final calibration. The same land surface model parameters were used for each zone. This was done because of the paucity of data that could be used to derive different parameters for the different zones.

There are a number of limitations of the modeling approach used, most of which are directly or indirectly related to data inadequacies.

Table 6. Final calibration coefficients and evapotranspiration data for Toutle River drainage above USGS Gauge 14-2425 (see Appendix A for variable definitions).

Drainage Area = 474 sq. miles

	Zone 1	Zone 2	Zone 3	Zone 4
Area Fractions	0.22	0.30	0.30	0.18
Multipliers for Precipitation (RAWT)	1.0	0.99	0.99	0.90

Model Parameters (same for all four zones)

	UZTW	UZFW	LZTW	LZFWS	LZFWP
Capacity[a]	2.0	2.0	6.0	6.0	6.0
Initial Content[a] (October 1, 1968)	1.80	0.10	4.50	0.60	4.0

UZ-K	LZS-K	LZP-K	ZPERC	REXP
0.280	0.070	0.009	14.0	1.40

SIDE	SSOUT	PCTIM	SARVA	RSERV
0	0	0.005	0.008	0.30

PBASE	ADIMP	ADIMC	PFREE
0.474	0.004	6.30	0.400

Mean Daily Potential Pan Evaporation[a]

OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP
.036	.028	.01	.01	.018	.030	.04	.095	.135	.155	.145	.105

[a] inches of water

The precipitation patterns estimated from the observed records do not necessarily represent actual conditions for two reasons. First, there is a difficulty in using point estimates to represent synoptic scale phenomena. Second, the point estimates themselves are not necessarily representative of basin conditions: there are no high elevation precipitation stations in the catchment. The temperatures used are also subject to error due to areal variability and poor areal coverage; consequently rain or snow events may be incorrectly identified. Model estimates of snow accumulation and ablation at high elevations are subject to considerable error as there are virtually no data to verify actual conditions. Finally, there are errors in both the model structure, resulting from the necessity to simplify the physical processes to avoid undue complexity, and in the calibration process. In this application, we believe that data inadequacies are the most important source of simulation errors.

Summary of Pre-Eruption Calibration - Toutle River

Any plausible model should satisfy annual and monthly water budgets, as well as model individual storm event hydrographs satisfactorily. The calibration period we used was from October 1968 through September 1976, (water years 1969-75), with verification from October 1976 through April 1980. Estimated and recorded annual budgets are given in Table 7. The annual average error during the calibration period was 2.1%, i.e., slightly more runoff was simulated than occurred. For the verification period the average error was less, approximately 1.0%, although from a statistical standpoint the difference in calibration and verification errors is probably not significant.

A typical monthly simulation summary for water year 1978 is given in Table 8. It is clear that the model poorly simulates the summer runoff response. The peak flood

Table 7. Annual water budget summary comparison, Toutle River.

	Water Year	Recorded Streamflow[a]	Simulated Streamflow[a]	Percentage Difference	Average Error Percent
Calibration Period	1969	4.80	4.80	-4.3	
	1970	3.97	4.31	8.5	
	1971	5.56	5.09	-8.4	
	1972	6.16	6.14	- .3	
	1973	3.34	3.45	3.3	
	1974	6.55	6.84	4.4	
	1975	4.32	4.58	6.1	
	1976	5.52	5.46	-1.1	2.1
Verification Period	1977	2.50	2.32	-7.1	
	1978	4.75	5.21	9.7	
	1979	3.08	3.01	.4	
	1980	3.59	3.63	1.0	1.0

[a] Average flow, cfs/square mile

Table 8. Monthly water budget summary comparison, water year 1978, Toutle River at USGS Gauge 14-2425.

Month	Recorded Streamflow	Simulated Streamflow	Percentage[a] Difference
October	1.92[b]	1.68[b]	-13
November	8.94	9.84	10
December	16.08	19.34	20
January	5.51	7.06	28
February	4.64	5.37	16
March	3.25	3.30	1
April	4.71	5.45	16
May	4.53	5.32	17
June	2.64	2.85	8
July	1.53	0.92	-40
August	1.23	0.61	-51
September	1.95	0.74	-62

---

[a] (Simulated-Recorded)/Simulated*100

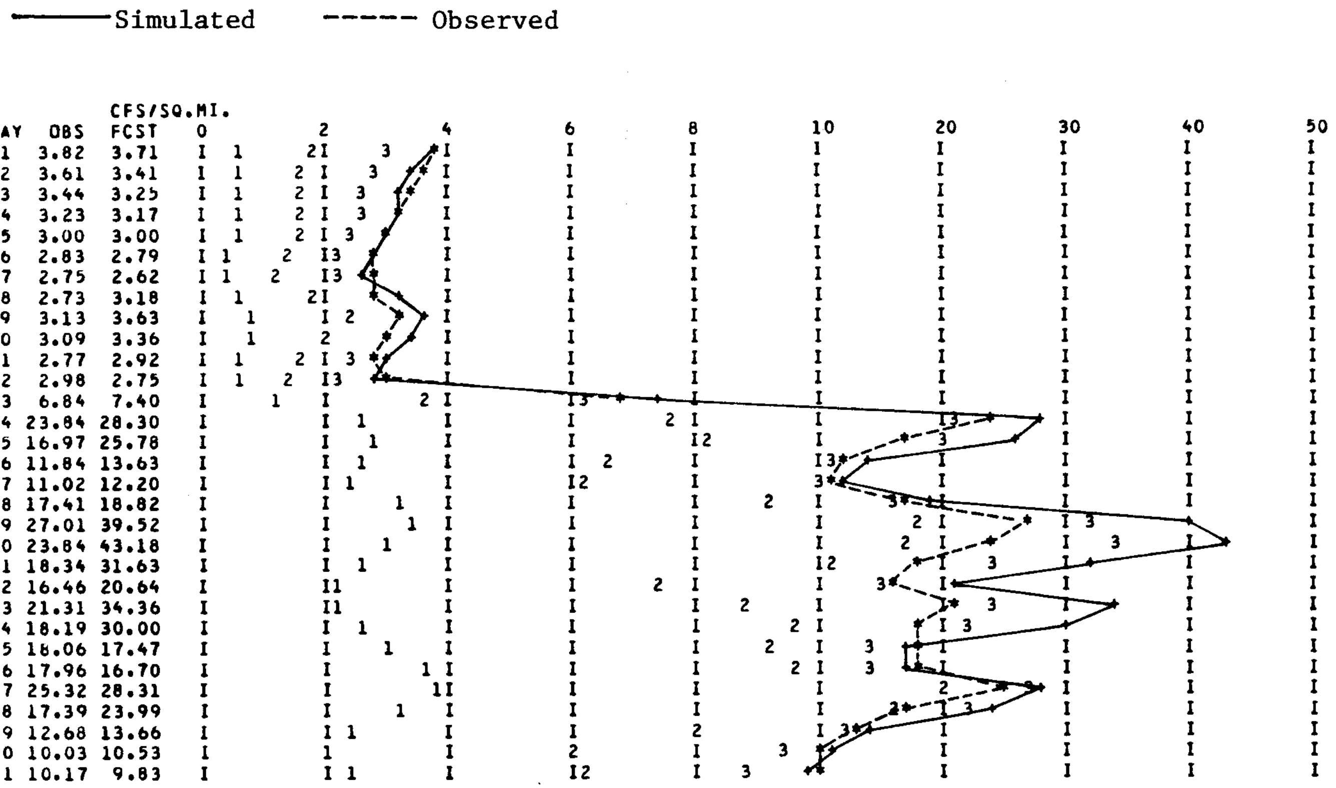
[b] Average flow, cfs/square mile

in water year 1978 occurred in December, 1977. Although the monthly runoff volume was oversimulated by approximately 20%, inspection of the average daily hydrograph shows that the model simulated the peak flood response quite satisfactorily. The complete hydrograph for this month is shown in Figure 12 which is discussed in detail below.

Individual hydrographs for the calibration period are shown in Figures 9, 10, and 11. Figure 9 shows simulated and recorded hydrographs for January 1970 (simulated results are under the heading FCST). The ordinates are in average cfs/square mile per day. Note that two linear scales 0-10 and 10-50 are used. For a given day the simulated results show 1, 2, 3 and +; recorded flows are shown with an asterik (*). Each symbol represents the accumulated runoff including the given zone, with the "+" indicating total simulated runoff for the basin. This display facilitates determination of the contribution of the various zones to basin runoff. It is clear from Figure 9 that the model does a satisfactory job until Jaunary 14 and oversimulates considerably from January 19 to January 29. Extensive review of similar plots and sensitivity tests suggest that such discrepancies are the result of errors in precipitation estimates.

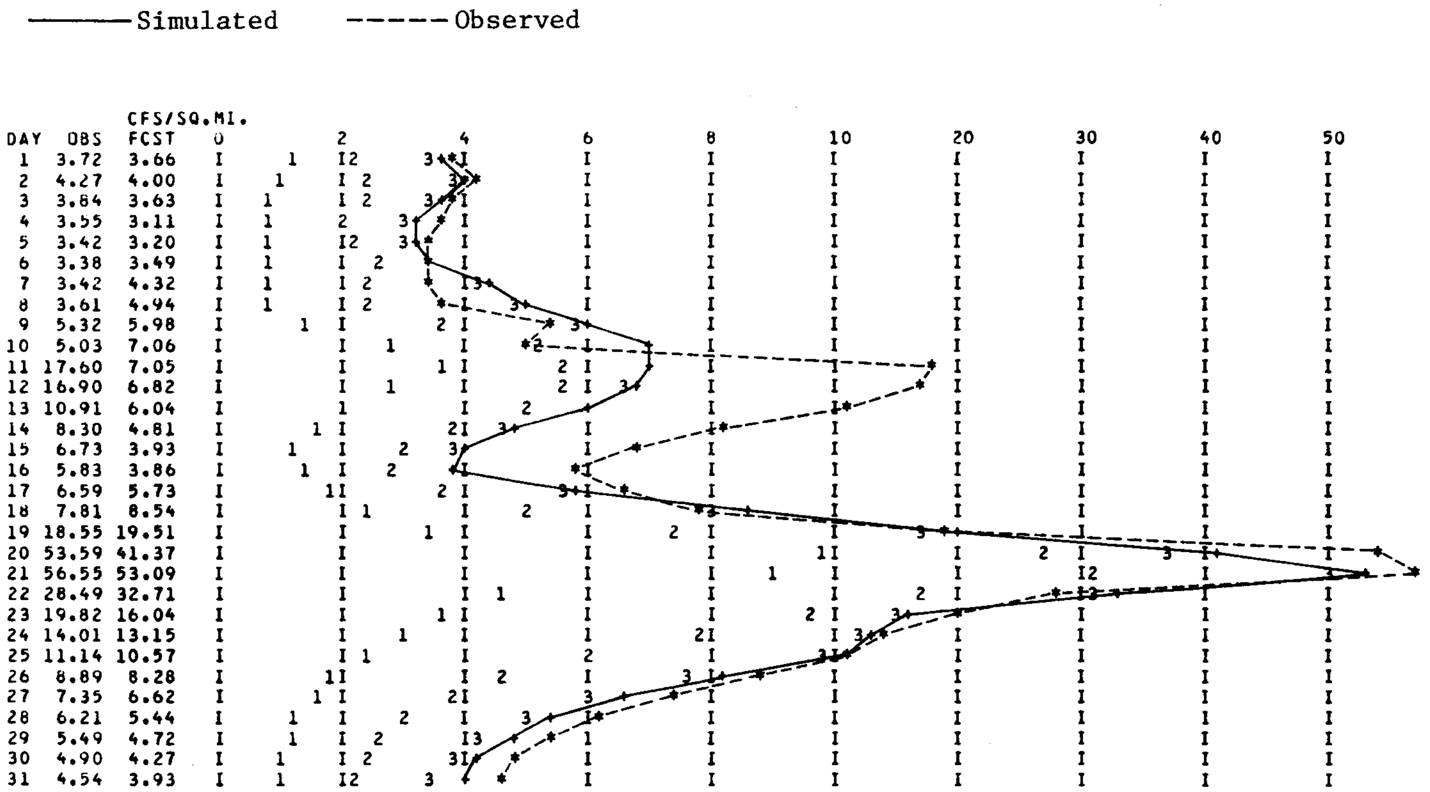
Figure 10 shows recorded and simulated hydrographs for January 1972. Here, one of the largest events of record (1930-80) is modeled quite satisfactorily. Finally Figure 11 shows the final calibration result for January 1974. It appears that the model tracks the gross runoff features quite satisfactorily.

Verification quality is displayed visually in Figure 12 (December 1977), Figure 13 (February 1978), and Figure 14 (January 1980). Given our interest in simulating major floods satisfactorily we have used these visual displays rather than computing summary performance statistics. These figures generally



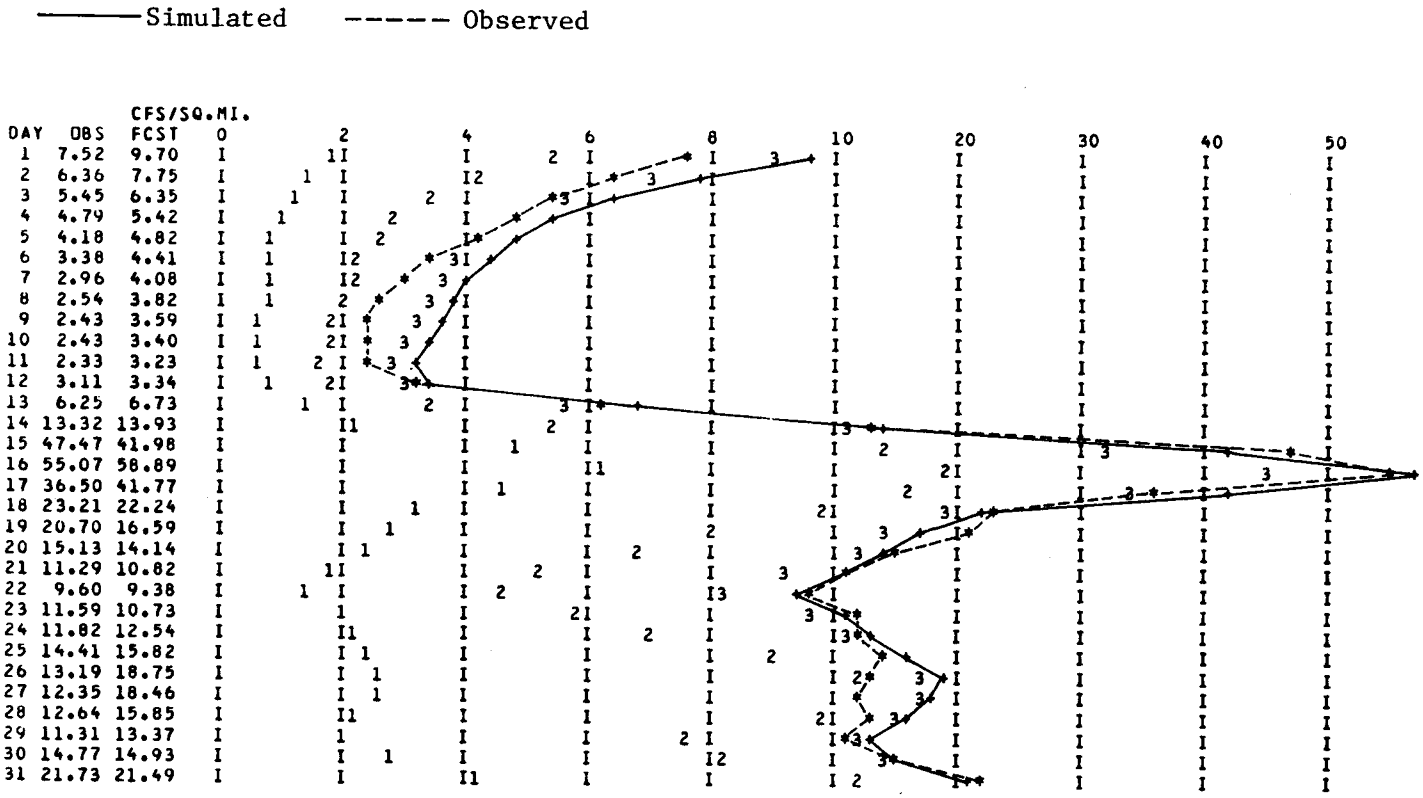
DAY	OBS	FCST
1	3.82	3.71
2	3.61	3.41
3	3.44	3.25
4	3.23	3.17
5	3.00	3.00
6	2.83	2.79
7	2.75	2.62
8	2.73	3.18
9	3.13	3.63
10	3.09	3.36
11	2.77	2.92
12	2.98	2.75
13	6.84	7.40
14	23.84	28.30
15	16.97	25.78
16	11.84	13.63
17	11.02	12.20
18	17.41	18.82
19	27.01	39.52
20	23.84	43.18
21	18.34	31.63
22	16.46	20.64
23	21.31	34.36
24	18.19	30.00
25	18.06	17.47
26	17.96	16.70
27	25.32	28.31
28	17.39	23.99
29	12.68	13.66
30	10.03	10.53
31	10.17	9.83

Figure 9. Calibration Period Recorded (OBS) and Simulated (FCST) Average Daily Flow for Toutle River near Silver Lake (USGS 14-2425), January, 1970.



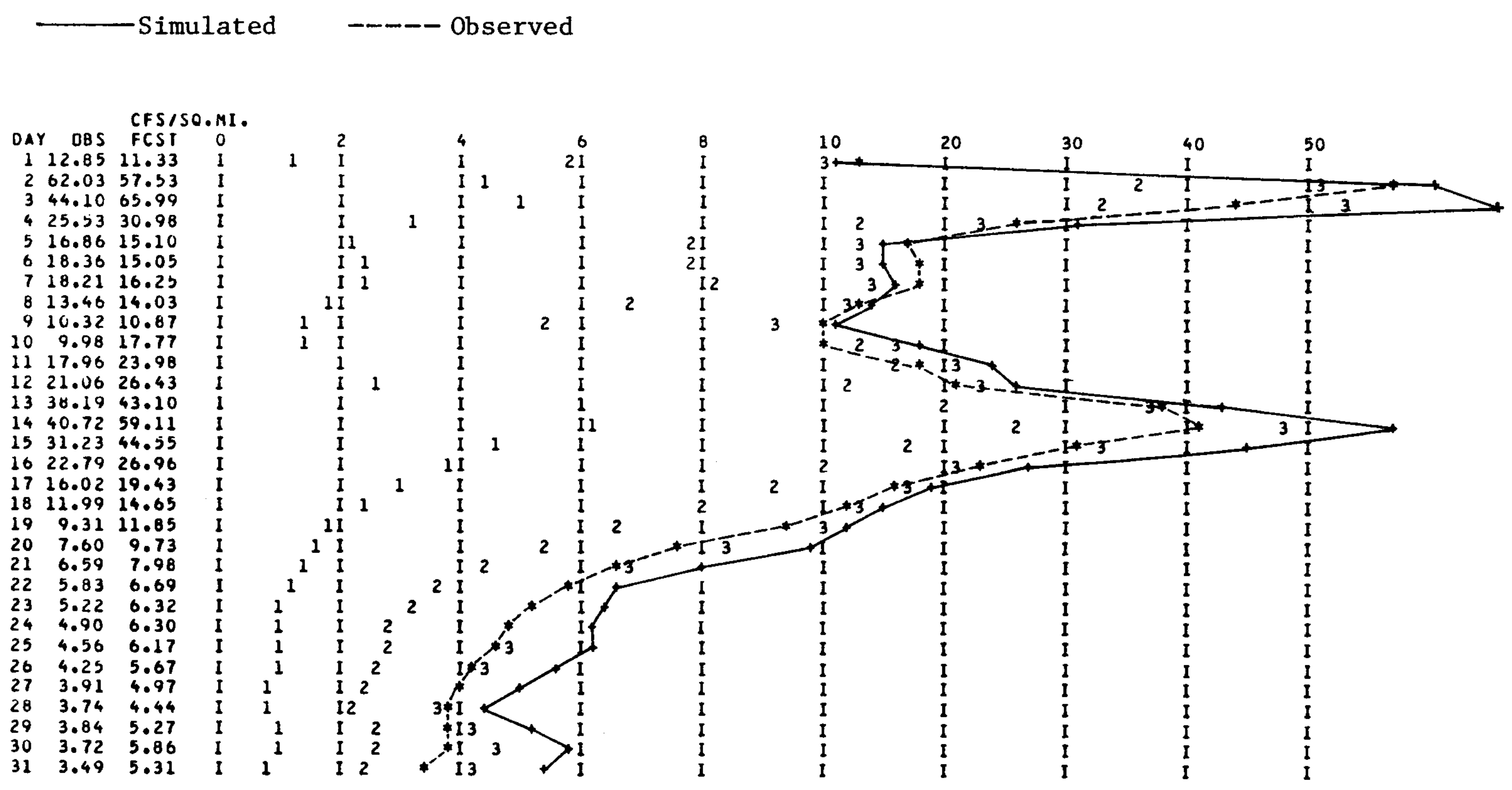
DAY	OBS	FCST
1	3.72	3.66
2	4.27	4.00
3	3.64	3.63
4	3.55	3.11
5	3.42	3.20
6	3.38	3.49
7	3.42	4.32
8	3.61	4.94
9	5.32	5.98
10	5.03	7.06
11	17.60	7.05
12	16.90	6.82
13	10.91	6.04
14	8.30	4.81
15	6.73	3.93
16	5.83	3.86
17	6.59	5.73
18	7.81	8.54
19	18.55	19.51
20	53.59	41.37
21	56.55	53.09
22	28.49	32.71
23	19.82	16.04
24	14.01	13.15
25	11.14	10.57
26	8.89	8.28
27	7.35	6.62
28	6.21	5.44
29	5.49	4.72
30	4.90	4.27
31	4.54	3.93

Figure 10. Calibration Period Recorded (OBS) and Simulated (FCST) Average Daily Flow for Toutle River near Silver Lake (USGS 14-2425), January, 1972.



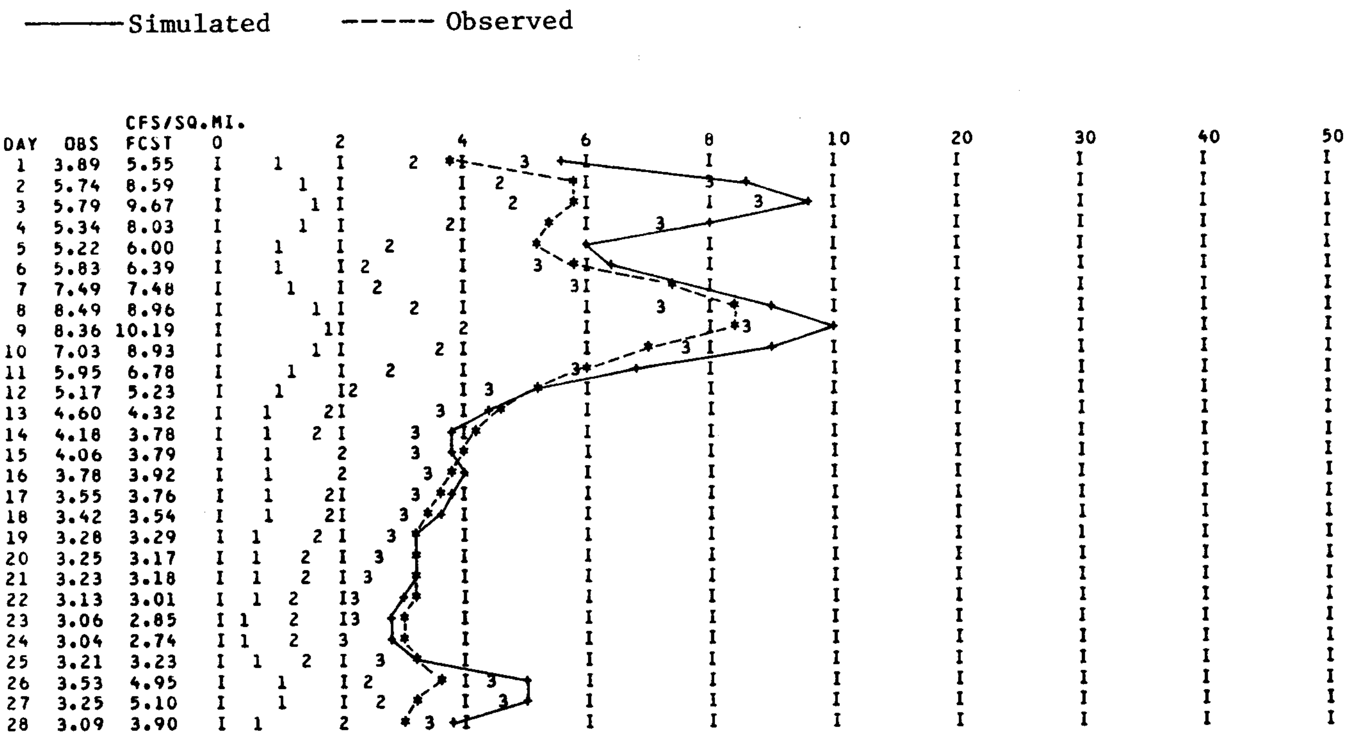
DAY	OBS	FCST
1	7.52	9.70
2	6.36	7.75
3	5.45	6.35
4	4.79	5.42
5	4.18	4.82
6	3.38	4.41
7	2.96	4.08
8	2.54	3.82
9	2.43	3.59
10	2.43	3.40
11	2.33	3.23
12	3.11	3.34
13	6.25	6.73
14	13.32	13.93
15	47.47	41.98
16	55.07	58.89
17	36.50	41.77
18	23.21	22.24
19	20.70	16.59
20	15.13	14.14
21	11.29	10.82
22	9.60	9.38
23	11.59	10.73
24	11.82	12.54
25	14.41	15.82
26	13.19	18.75
27	12.35	18.46
28	12.64	15.85
29	11.31	13.37
30	14.77	14.93
31	21.73	21.49

Figure 11. Calibration Period Reocrded (OBS) and Simulated (FCST) Average Daily Flow for Toutle River near Silver Lake (USGS 14-2425), January, 1974.



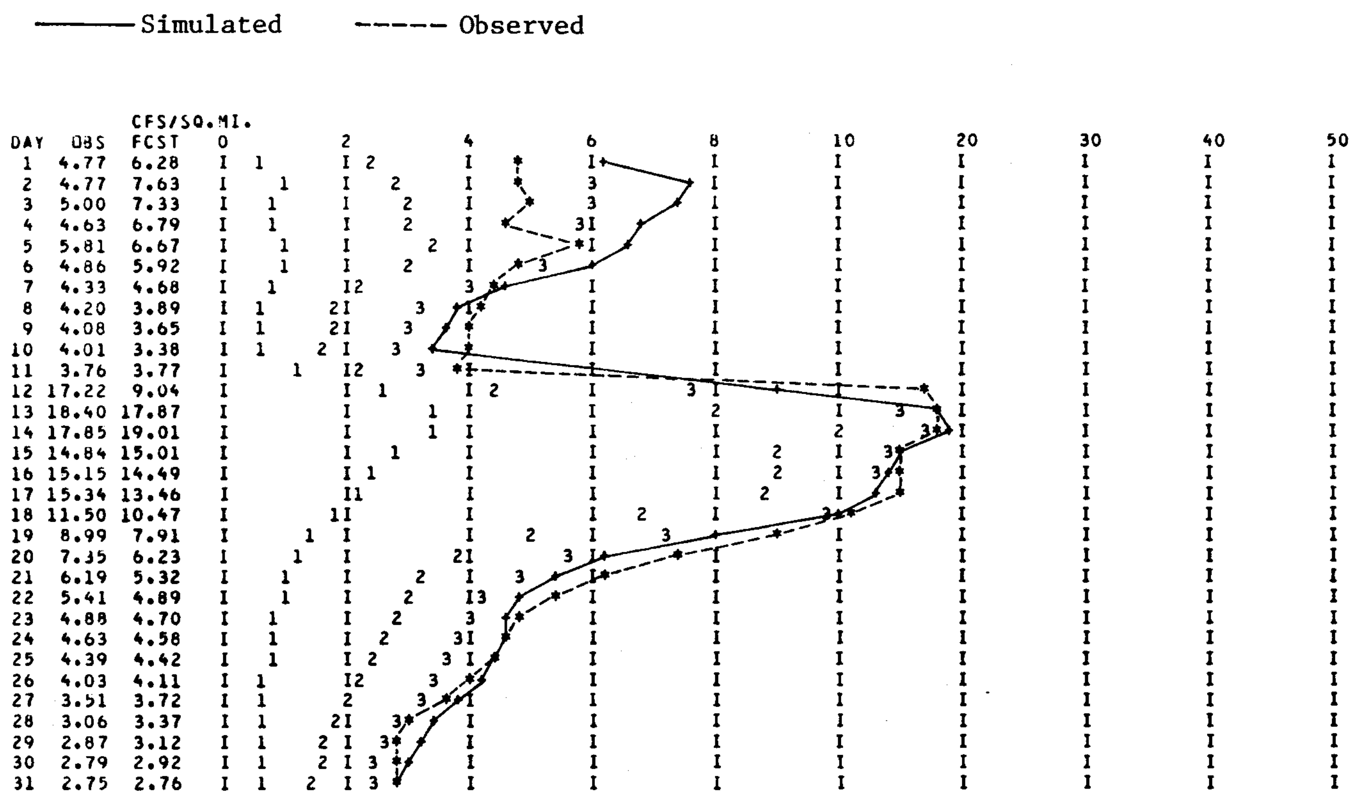
DAY	OBS	FCST
1	12.85	11.33
2	62.03	57.53
3	44.10	65.99
4	25.53	30.98
5	16.86	15.10
6	18.36	15.05
7	18.21	16.25
8	13.46	14.03
9	10.32	10.87
10	9.98	17.77
11	17.96	23.98
12	21.06	26.43
13	38.19	43.10
14	40.72	59.11
15	31.23	44.55
16	22.79	26.96
17	16.02	19.43
18	11.99	14.65
19	9.31	11.85
20	7.60	9.73
21	6.59	7.98
22	5.83	6.69
23	5.22	6.32
24	4.90	6.30
25	4.56	6.17
26	4.25	5.67
27	3.91	4.97
28	3.74	4.44
29	3.84	5.27
30	3.72	5.86
31	3.49	5.31

Figure 12. Verification Period Recorded (OBS) and Simulated (FCST) Average Daily Flow, for Toutle River near Silver Lake (USGS 14-2425), December, 1977.



DAY	OBS	FCST
1	3.89	5.55
2	5.74	8.59
3	5.79	9.67
4	5.34	8.03
5	5.22	6.00
6	5.83	6.39
7	7.49	7.48
8	8.49	8.96
9	8.36	10.19
10	7.03	8.93
11	5.95	6.78
12	5.17	5.23
13	4.60	4.32
14	4.18	3.78
15	4.06	3.79
16	3.78	3.92
17	3.55	3.76
18	3.42	3.54
19	3.28	3.29
20	3.25	3.17
21	3.23	3.18
22	3.13	3.01
23	3.06	2.85
24	3.04	2.74
25	3.21	3.23
26	3.53	4.95
27	3.25	5.10
28	3.09	3.90

Figure 13. Verification Period Recorded (OBS) and Simulated (FCST) Average Daily Flow, for Toutle River near Silver Lake (USGS 14-2425), February, 1978.



DAY	OBS	FCST
1	4.77	6.28
2	4.77	7.63
3	5.00	7.33
4	4.63	6.79
5	5.81	6.67
6	4.86	5.92
7	4.33	4.68
8	4.20	3.89
9	4.08	3.65
10	4.01	3.38
11	3.76	3.77
12	17.22	9.04
13	18.40	17.87
14	17.85	19.01
15	14.84	15.01
16	15.15	14.49
17	15.34	13.46
18	11.50	10.47
19	8.99	7.91
20	7.35	6.23
21	6.19	5.32
22	5.41	4.89
23	4.88	4.70
24	4.63	4.58
25	4.39	4.42
26	4.03	4.11
27	3.51	3.72
28	3.06	3.37
29	2.87	3.12
30	2.79	2.92
31	2.75	2.76

Figure 14. Verification Period Recorded (OBS) and Simulated (FCST) Average Daily Flow, for Toutle River near Silver Lake (USGS 14-2425), January, 1980.

indicate that time shifts (most precipitation stations report at 7:00 a.m., rather than midnight) between recorded and simulated events on the order of one day are common (but not systematic) reflecting the different data reporting and averaging periods. This data time shift difference, coupled with response time on the order of six hours, indicates why hydrograph summary statistics such as means and variances of daily runoff errors can be misleading.

Cispus Drainage Basin

The Cispus River Catchment was modeled for the area above U.S.G.S. Gauge 14-2325 near Randle. The land elevation ranges from over 12,000 ft at Mt. Adams, to 1,222 ft at the gauge. Because this elevation range is so large, it was initially decided to divide the basin into five elevation zones. Four weather stations were used to provide data for the Snow Accumulation and Ablation Model: Rainier Paradise, Rainier Longmire, Rainier Ohanapecosh, and Kid Valley. It soom became apparent, however, that five zones resulted in too many calibration parameters to evaluate effectively. One problem in this regard was the lack of good snow course data for calibration of the Snow Ablation Model. Only one snow course station lies near the basin (White Pass), and this snow course receives much more snow than is representative for the rest of the basin. In the absence of good snow water equivalent records, the parameters of the snow model must be inferred from the runoff calibration error, which is at best difficult. An even more significant problem is the lack of any precipitation stations within the basin.

In consideration of these difficulties, it was decided to reduce the number of elevation zones to two (of equal area), and use the two weather stations thought to be most representative of the basin. Kid Valley precipitation and temperature data were used for zone 1 and Longmire for zone 2. These stations were both far outside the basin, approximately 50 and 35 miles away from the center of the catchment respectively; they were, however, the closest stations with the required data base.

The difficulties encountered in calibrating the Cispus Basin were similar to those described for the Toutle River, with some additional complications. The mean elevation of the Toutle Basin is much lower than the Cispus, and there is a low elevation weather station (Kid Valley) located within the catchment area. Kid Valley is also the only low elevation station suitable for modeling the Cispus. Unfortunately it is separated by 50 miles and numerous north-south oriented ridges from the center of the Cispus Basin. Because the general direction of frontal storm movements is southwest to northeast, these ranges introduce considerable areal variability into daily rainfall patterns, which, in addition to the remote location of the station, reduce its representativeness.

The available high elevation stations (Rainier Longmire, Ohanapecosh and Paradise) are all located near Mt. Rainier and are influenced by the local topography there, and are also separated by 35 miles and numerous ridges from the basin center. Higher elevation precipitation records are also much more susceptible to wind related measurement error, so that the recorded precipitation could be much different (generally less) than what actually occurred.

For these reasons, the calibrations for the Cispus River were generally less satisfactory than those observed for the Toutle. The only consolation in the Cispus modeling effort was that the hydrologic impacts of the eruption on this basin were much less severe than on the Toutle, so although calibration errors may be large, the practical implications of those errors are small, in that changes in flood response of the basin (Chapter V) are expected to be minor.

Because the station elevations were much lower than the zone elevations (see Table 9), multipliers were used on the station precipitation as described in Chapter III to approximate the zonal precipitation. Temperature adjustment was used to scale down the station temperature to represent the elevation zone temperatures. Both precipitation and temperature correction factors were subsequently further adjusted during the calibration process. An important difference from the approach used in modeling the Toutle was that runoff from the individual elevation zones was not modeled independently, rather the weighted psuedo-precipitation records from the snow model were used to drive the soil moisture accounting model. This approach was taken due to difficulties in calibration and in identifying areal variations in ash cover between the elevation zones.

Table 9. Precipitation and temperature data used for the Cispus Catchment. Input to Snow Ablation and Accumulation Model.

Zone	Mean Elev. (feet)	Subcatchment Area Fraction[a]	Precip & Temp. Sta.	Sta. Elev. (feet)	Multiplier	Temp. Increment[b]
1	3300	0.50	Kid Valley	690	1.4	-3.4°C
2	4650	0.50	Longmire	2760	1.2	-2.6°C

[a] Drainage area above USGS Gauge 14-2325 = 321 square miles

[b] "Temperature increment" is the lapse rate multiplied by the elevation difference between the station and the zone

The model calibration process was carried out as described for the Toutle River simulations. The final calibration parameters for the Streamflow Simulation Model are given in Table 10.

Table 10. Final calibration coefficients and evapotranspiration data for the Cispus River drainage above USGS Gauge 14-2325 (see Appendix A for variable definitions).

Drainage Area = 321 square miles

	Zone 1	Zone 2
Area Weights	0.46	0.44

Model Parameters (same for both zones)

		UZTW	UZFW	LZTW	LZFWS	LZFWP
Storage Zones	Capacity(a)	2.00	2.00	6.00	3.00	6.00
	Initial Contents(a)	1.80	0.10	4.50	0.60	4.00

Parameters	UZ-K	LZS-K	LZP-K	ZPERC	REXP
	0.280	0.070	0.009	14.0	1.40
	SIDE	SSOUT	PCTIM	SARVA	RSERV
	0	0	0.004	0.008	0.30
		PBASE	ADIMP	ADIMC	PFREE
		0.264	0.004	6.30	0.500

Mean Daily Potential Pan Evaporation(a)

OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP
.036	.028	.01	.01	.018	.030	.04	.095	.135	.155	.145	.105

(a) inches of water

Summary of Pre-Eruption Calibration and Verification - Cispus River

The calibration period for the Cispus River was from October 1974 to September 1978 (Water Years 1975-78). The verification period consisted of Water Years 1968-74 and 1979-80. The annual budget summary is given in Table 11. The average annual error for the entire period was -0.7%.

Table 11. Annual water budget summary, Cispus River.

	Water Year	Recorded Streamflow[a]	Simulated Streamflow[a]	Difference	Average Error Percent
Calibration Period	1975	60.49	53.05	-12.3	
	1976	68.62	73.15	6.6	
	1977	30.41	26.30	13.5	
	1978	58.86	64.03	8.8	
Verification Period	1968	57.56	67.26	16.9	
	1969	63.04	59.66	- 5.4	
	1970	53.15	50.15	- 5.6	
	1971	72.56	69.53	- 4.2	
	1972	83.09	80.61	- 3.0	
	1973	42.59	41.33	- 3.7	
	1974	88.83	80.74	- 9.1	
	1979	39.29	38.59	- 1.8	
	1980	52.48	47.24	-10.0	-0.7%

[a] Average flow, cfs/square mile

A typical monthly water budget summary is given in Table 12 for water year 1979. As with the Toutle, the model poorly simulates the summer runoff. Individual hydrographs for the calibration period are shown in Figures 15 and 16. As these figures show, the peaks are generally undersimulated, suggesting that Kid Valley and Longmire precipitation stations do not represent the precipitation accurately in the Cispus Basin. It is not possible, however, to scale up the precipitation further (use a larger multiplier) without exceeding the annual balance.

Table 12. Monthly water budget summary comparison, Water Year 1979, Cispus River.

Month	Recorded Streamflow[a]	Simulated Streamflow[a]	Percentage Difference
Oct	1.36	0.84	-38.2
Nov	1.50	2.48	65.3
Dec	2.46	2.48	0.8
Jan	1.50	1.19	-20.7
Feb	3.61	3.17	-12.2
Mar	5.82	4.67	-19.8
Apr	4.45	5.31	19.3
May	9.06	11.64	28.5
Jun	4.26	3.54	-16.9
Jul	2.35	1.20	-48.9
Aug	1.56	0.76	-51.3
Sep	1.36	1.31	- 3.7

[a] Average flow in cfs/square mile

Figures 17-19 show verification period simulations for November 1968; January 1969; and December 1979. A review of these figures, along with other verification period results, indicated that the performance of the model during the verification period, although less than desirable, was compatible with the calibration period results.

——— Simulated ------ Observed

		CFS/SQ.MI.	
DAY	PCP	OBS	FCST
1	.63	4.21	5.17
2	1.01	8.85	7.63
3	0.00	6.11	7.15
4	0.00	4.68	4.65
5	.04	3.90	3.14
6	.24	3.31	2.57
7	.19	3.34	2.97
8	.01	2.90	3.06
9	0.00	2.71	2.63
10	.40	3.56	3.25
11	.34	3.87	4.29
12	.27	3.87	4.65
13	.47	4.18	5.28
14	.45	4.93	6.16
15	.13	6.20	5.47
16	.25	6.42	4.93
17	.05	5.49	4.27
18	0.00	4.71	3.29
19	0.00	4.02	2.78
20	0.00	3.40	2.51
21	0.00	3.05	2.33
22	0.00	2.93	2.20
23	.32	2.81	2.14
24	.12	2.76	2.67
25	1.15	9.23	6.17
26	.87	17.33	9.91
27	.40	12.22	10.20
28	.17	9.57	7.93
29	.77	11.13	8.25
30	.05	9.79	7.91

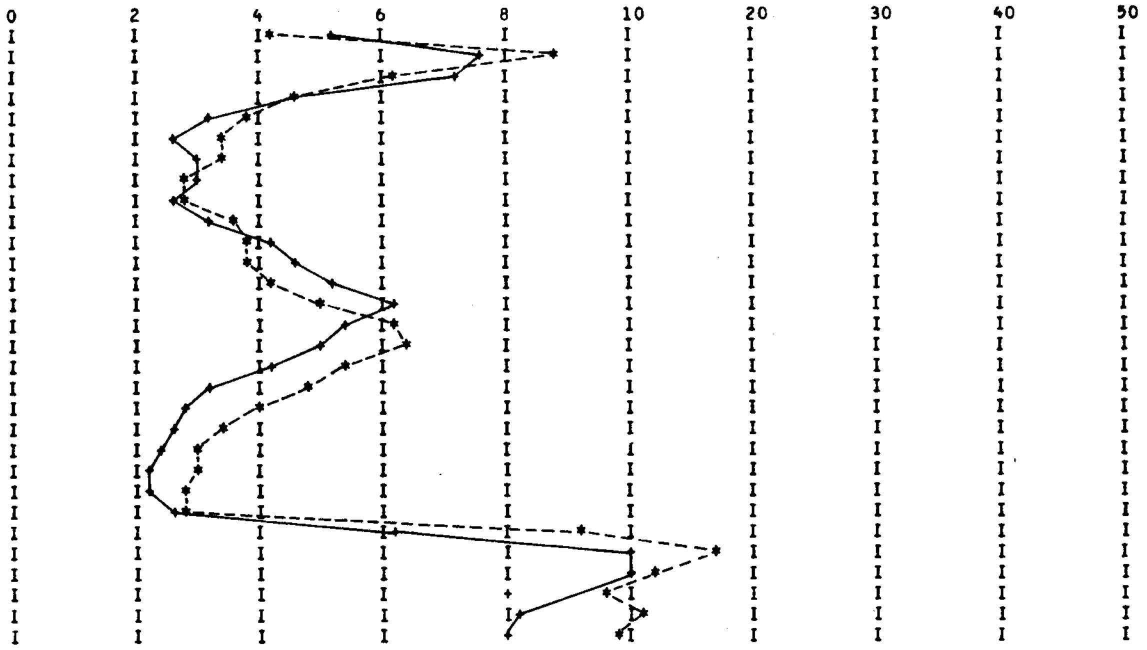


Figure 15. Calibration Period Recorded (OBS) and Simulated (FCST), Average Daily Flow for Cispus River near Randle (USGS 14-2325), November, 1977.

——— Simulated ------Observed

DAY	PCP	CFS/SQ.MI. OBS	FCST
1	.61	5.11	5.65
2	1.15	23.00	9.21
3	1.58	33.96	14.25
4	1.63	32.09	23.31
5	1.16	42.37	25.96
6	.04	20.25	18.81
7	0.00	13.40	12.20
8	1.14	14.34	12.29
9	.55	15.18	14.20
10	.21	13.53	12.75
11	.06	11.25	10.18
12	.02	9.48	8.11
13	0.00	8.10	6.50
14	0.00	7.08	5.38
15	0.00	6.11	4.69
16	.02	5.55	4.25
17	.03	5.05	3.94
18	0.00	4.55	3.66
19	0.00	4.21	3.44
20	0.00	3.90	3.27
21	0.00	3.68	3.11
22	.03	3.43	2.97
23	.37	3.34	3.93
24	.39	3.56	5.49
25	.40	4.46	6.64
26	.32	4.55	7.09
27	.59	9.79	7.98
28	.27	11.19	8.26
29	.42	8.85	8.19
30	.22	9.13	7.83
31	.76	10.16	8.86

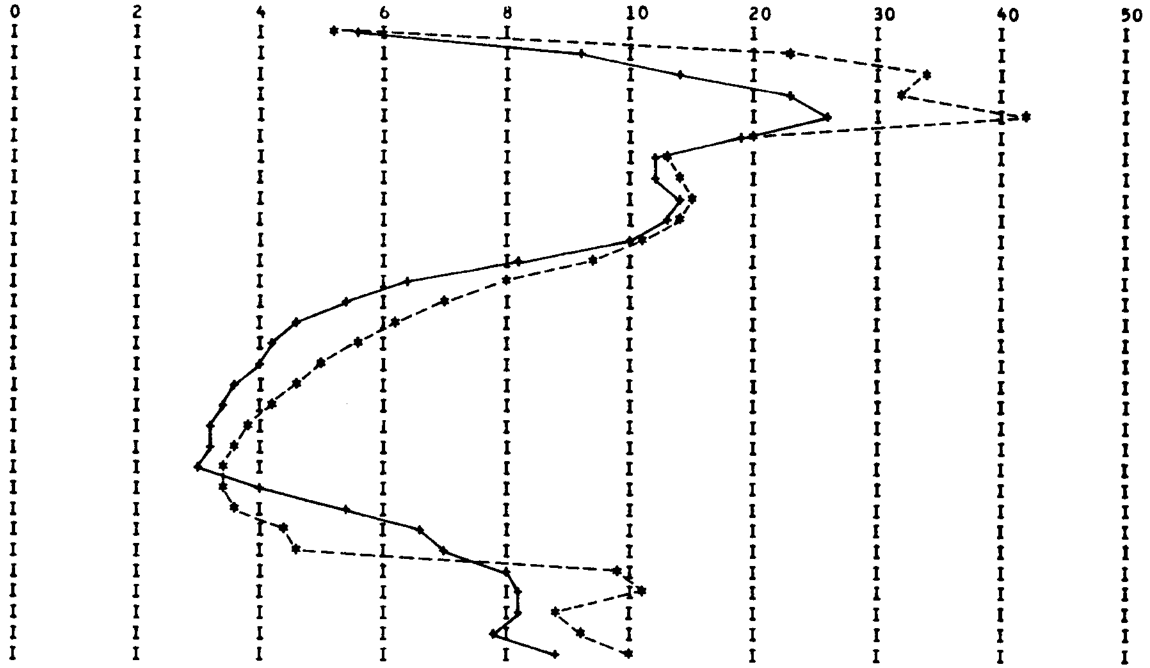


Figure 16. Calibration Period Reocrded (OBS) and Simulated (FCST), Average Daily Flow, for Cispus River near Randle (USGS 14-2325), December, 1975.

——— Simulated   - - - - - Observed

		CFS/SQ.MI.	
DAY	PCP	OBS	FCST
1	.34	3.90	4.86
2	.21	4.15	4.77
3	.03	3.93	4.40
4	.01	3.71	3.77
5	.03	3.46	3.17
6	.17	3.21	2.89
7	1.77	4.49	7.82
8	.60	10.47	12.76
9	.20	8.82	11.33
10	1.98	17.45	13.57
11	.65	20.57	17.42
12	.05	13.74	14.83
13	0.00	10.22	10.30
14	.10	8.23	7.56
15	.06	6.89	6.07
16	.09	5.99	5.26
17	.13	6.33	4.90
18	.04	6.73	4.62
19	.31	6.80	5.21
20	.13	7.39	5.26
21	.71	11.50	6.99
22	.07	10.94	7.46
23	.31	9.20	6.92
24	.03	7.70	6.06
25	.16	6.73	5.00
26	.40	6.11	5.88
27	.01	5.64	5.84
28	.43	5.46	6.00
29	.05	5.11	5.74
30	.19	4.77	4.90

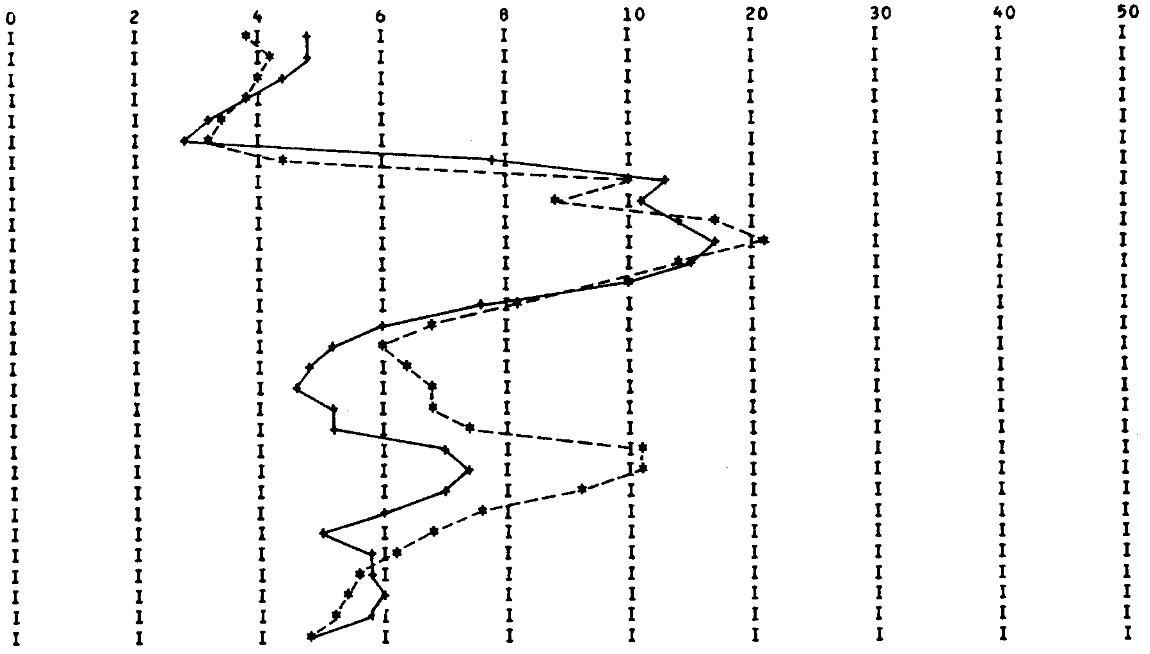


Figure 17. Calibration Period Recorded (OBS) and Simulated (FCST), Average Daily Flow, for Cispus River near Randle (USGS 14-2325), November, 1968.

		CFS/SQ.MI.	
DAY	PCP	OBS	FCST
1	.09	3.31	2.74
2	.11	3.34	2.72
3	.18	3.34	2.84
4	.31	4.27	3.92
5	1.41	14.09	7.85
6	.86	15.71	11.88
7	.46	17.33	12.14
8	.02	12.90	9.26
9	0.00	10.13	6.35
10	0.00	8.35	4.62
11	0.00	7.08	3.78
12	0.00	6.14	3.35
13	0.00	5.49	3.07
14	0.00	5.02	2.85
15	0.00	4.65	2.69
16	0.00	4.30	2.57
17	0.00	3.99	2.45
18	0.00	3.71	2.34
19	0.00	3.53	2.24
20	0.00	3.34	2.15
21	0.00	3.15	2.06
22	0.00	2.98	1.97
23	0.00	2.84	1.89
24	0.00	2.70	1.82
25	0.00	2.62	1.75
26	0.00	2.62	1.69
27	0.00	2.56	1.63
28	0.00	2.46	1.57
29	0.00	2.39	1.52
30	0.00	2.36	1.47
31	0.00	2.34	1.42

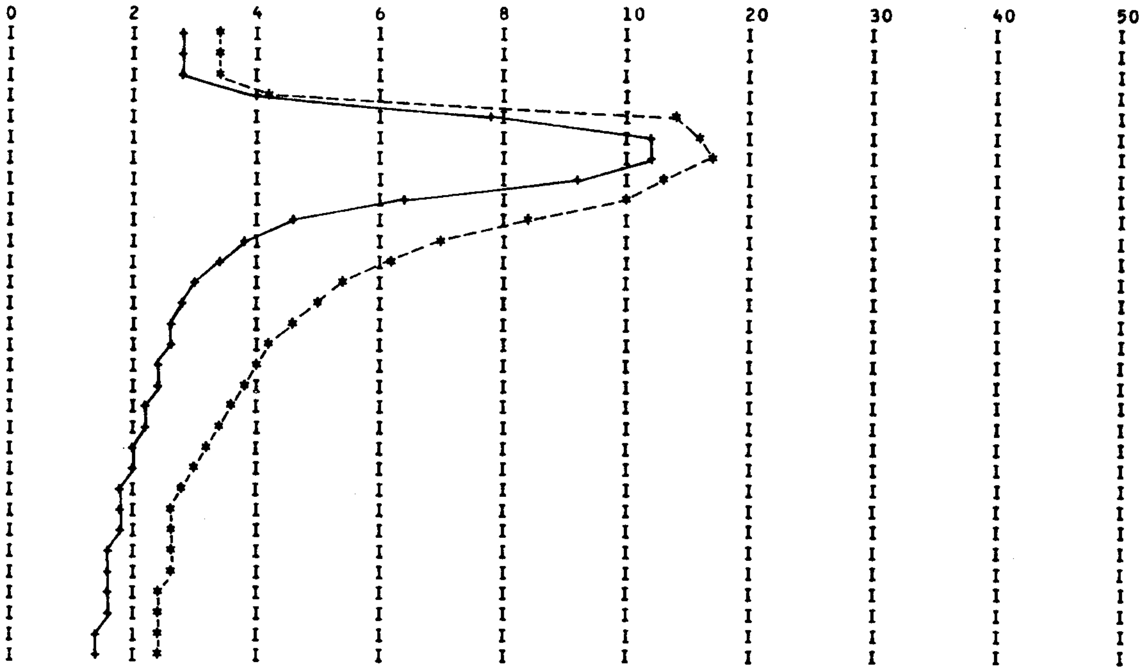


Figure 18. Verification Period Recorded (OBS) and Simulated (FCST), Average Daily Flow, for Cispus River near Randle (USGS 14-2325), January, 1969.

DAY	PCP	CFS/SQ.MI. OBS	CFS/SQ.MI. FCST
1	.06	1.21	.83
2	.49	1.28	2.08
3	.70	3.43	4.26
4	.13	3.12	4.11
5	1.76	8.67	7.29
6	.18	7.64	9.17
7	.01	5.86	6.52
8	.14	5.30	4.22
9	.07	4.80	3.42
10	.17	4.83	3.19
11	.27	5.21	3.91
12	.01	4.62	3.55
13	.36	4.30	3.78
14	0.00	3.96	3.53
15	.01	3.87	2.75
16	.35	5.33	3.38
17	.03	5.99	3.30
18	.82	6.55	5.17
19	1.89	11.31	10.80
20	.49	13.06	13.96
21	.68	14.62	13.27
22	.13	12.56	10.53
23	.04	9.66	7.66
24	.03	7.79	5.77
25	.09	6.61	4.73
26	.10	5.67	4.35
27	.11	5.02	4.24
28	.03	4.58	3.97
29	.01	4.24	3.59
30	.03	3.90	3.22
31	.07	3.71	3.01

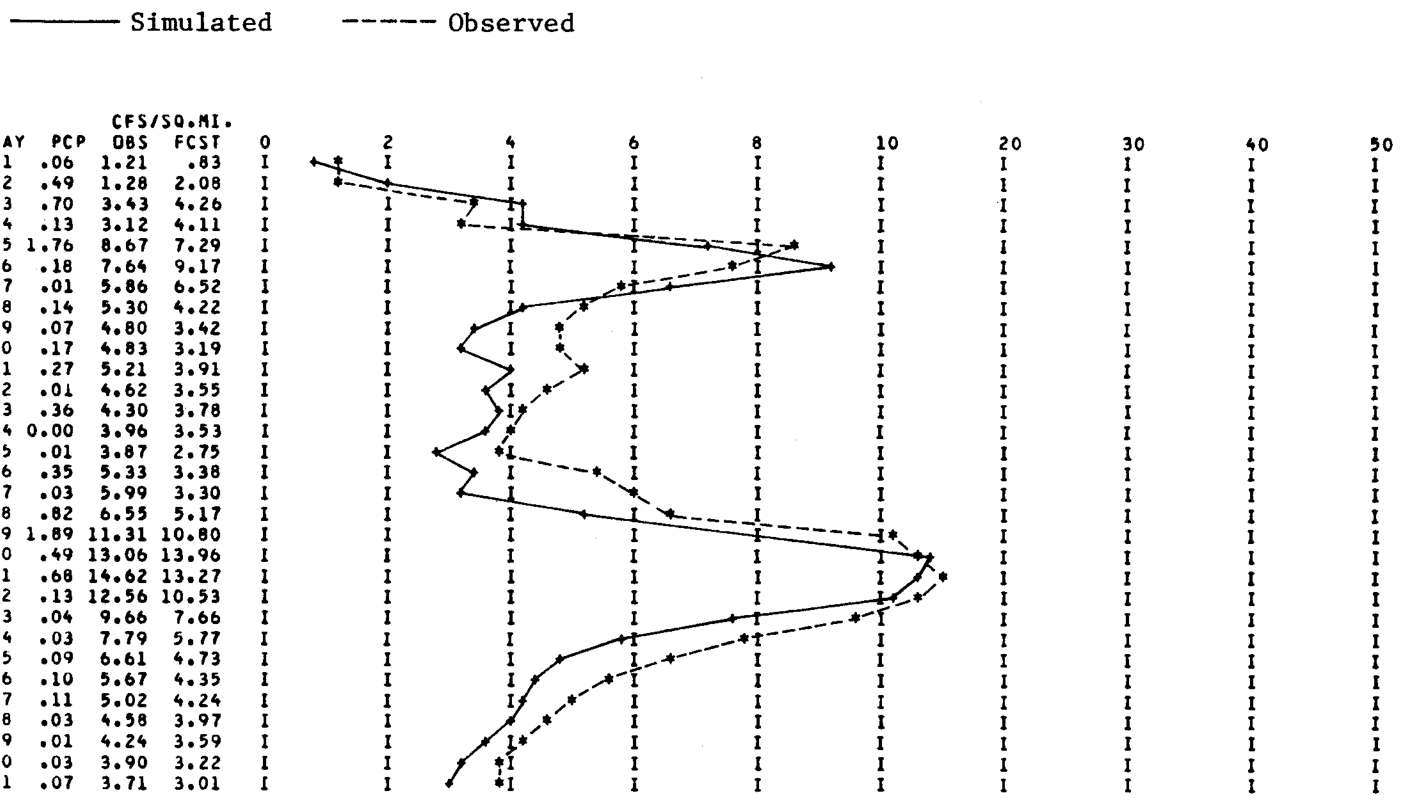


Figure 19. Verification Period Recorded (OBS) and Simulated (FCST), Average Daily Flow, for Cispus River near Randle (USGS 14-2325), December, 1979.

CHAPTER V.

FLOOD FREQUENCY CHANGES

The rainfall/runoff model, calibrated as described in Chapter IV, was adjusted to reflect the authors' perception of post-eruption conditions. As noted in Chapter I, it was not possible to recalibrate the model since there were no post-eruption flood events at the time the analysis was performed. Subsequently, a flood occured during December, 1980, which allowed preliminary verification of our predictions.

No changes were made in the snowmelt model for post-eruption conditions. Although elimination of vegetation at the higher elevations in the catchment has undoubtedly changed ablation patterns, and snow accumulation patterns to a lesser extent, no post eruption snow course data existed suitable for recalibration of the model. Insofar as most major floods occur in late fall and early winter, changes in ablation are less important for flood prediction than they would be, for instance, for spring runoff prediction.

Rainfall-Runoff Parameter Adjustment

Adjustment of model parameters was accomplished through review of photographs and maps comparing pre- and post-eruption conditions. These were then referenced to the various elevation zones. Two sets of estimates of post-eruption parameters were made; a best estimate and a worst case. The parameters modified for the Toutle River predictions are given in Table 13. Elevation zones 3 and 4 were extensively affected by the blast, including deposit of blast material, removal of trees and other vegetation, and deposition of ash, pyroclastic materials, and mudflows. These changes are reflected in the post eruption parameter sets.

Unfortunately, the rainfall-runoff model contains no parameters directly representing infiltration, the hydrologic process most affected by the eruption. Instead, infiltration is determined indirectly as the product of a percolation demand term and the fractional upper zone free water (constants/capacity). The percolation demand is the sum of the maximum rate at which water can drain from the lower zones (contribution to base flow) and a dry weather supplement related to the complement of the fractional lower zone contents (fraction empty) raised to a power. Although this structure is thought to be a realistic representation of the movement of water through a soil column, it results in a high degree of interdependency in parameters. For instance, rainfall reaching the soil column is assumed initially to satisfy the tension water deficit, then to contribute to upper zone free water storage, from which deep infiltration occurs. Therefore, a reduction in the capacity of the tension water zone has the effect of increasing direct runoff, since any water reaching the upper free zone in excess of infiltration capacity, when the upper zone capacity has been reached, contributes directly to runoff. However, this will also increase infiltration under conditions where a larger tension water zone would not have filled. The issue is complicated further since the tension water zone is used to represent water in soil tension, as well as that permanently ponded (removed by evaporation only). Especially in those areas of the upper basin where natural outflow channels were blocked, and where downed trees and ashfall created the potential for ponding, there is a question as to whether tension water storage capacity was increased or decreased following the eruption.

Given these complications, a more straightforward method of decreasing infiltration was simply to increase the fraction of impervious area (PCTIM), treating a fraction of each elevation zone as if it were completely impervious.

Thus, the worst case conditions assumed a relatively high fraction of equivalent impervious area. Generally, the philosophy for the worst case was to treat the affected zones of the watershed as highly impervious, with minimal recognition of changes in surface detention which would have had an opposing effect on runoff response. The best estimate, on the other hand, considers a more modest equivalent impervious area, with a substantial increase in tension water storage in zones 2 and 3, and coincident reduction in upper zone free water. The reduction in free water reflects a hypothesis that very little water can be stored in the upper soil layer in those areas where the land surface was most heavily affected by the blast.

Simulation Results - Toutle River

Figures 20-22 show selected months with moderate, intermediate, and large peak flows, simulated for pre-eruption, best estimate, and worst case conditions. From these figures, the most apparent predicted changes in runoff response are an increase in peak flows and a reduction in base flow. The increase in peak flows is greatest for moderate storms, where the contribution of increased impervious area to runoff is of greatest importance. For more intense storms leading to the largest floods, the upper soil moisture zones are usually filled or nearly so under pre-eruption conditions, and the contribution of rainfall to direct runoff is much higher. Therefore, increasing the impervious area has less effect for these events, since infiltration is a less significant process. Confirmation of this result can be obtained by estimating runoff coefficients for the largest floods, using precipitation multipliers from the snowmelt and rainfall-runoff models. Runoff coefficients, so computed on a daily basis, are as high as 0.8 under pre-eruption conditions.

This suggests that for the largest floods, the watershed acted much like an impervious surface prior to the eruption.

Table 14 shows the results of the analysis for seven flood events. The four largest of these (January, 1972; January, 1974; December, 1975; and December, 1977) were also four of the five largest annual floods of the entire historic record dating to 1930. The remaining flood in this group (December, 1933) is the daily flood of record with discharge of 31,000 cfs (although the January, 1972 flood had a higher instantaneous discharge, our attention here is focused on daily average flows, as this is the model time scale). The computed response ratio (ratio of predicted post eruption flood flow to historic recording) can provide some insight into the characteristics of the individual events (Table 14). Generally, the response ratios for the four largest floods shown in Table 14 are highest for December floods. This reflects the extreme importance of antecedent conditions in rainfall-runoff dynamics; both the large December floods occurred early in the month (December 4, 1975, and December 2, 1977, respectively) while the January 1972 and 1974 floods were in the second half of the month. The December floods were both preceeded by moderate rainfall, therefore antecedent soil moisture, following the summer dry period, was relatively low. As the impervious area was increased to reflect post-eruption conditions, a substantial amount of the effective precipitation which under historic conditions satisfied the soil moisture deficit instead was caused to contribute directly to runoff. The January floods, on the other hand, occurred under conditions of high antecedent precipitation, therefore the model treated much of the intensive rainfall leading to these floods as contributing to direct runoff under pre-eruption conditions, therefore increasing the impervious area had a lesser effect on runoff response.

Table 13. Altered Rainfall-runoff model parameters for Toutle River.

PCTIM

Zone	Pre-Eruption	Best Estimate	Worst Case
1	0.005	0.05	0.10
2	0.005	0.10	0.50
3	0.005	0.35	1.0
4	0.005	0.90	1.0

UZTW

Zone	Pre-Eruption	Best Estimate	Worst Case
1	2.0	2.0	2.0
2	2.0	6.0	4.0
3	2.0	6.0	2.0
4	2.0	2.0	2.0

UZFW

Zone	Pre-Eruption	Best Estimate	Worst Case
1	2.0	2.0	2.0
2	2.0	0.1	0.1
3	2.0	0.1	2.0
4	2.0	0.1	2.0

Table 14. Historic and Estimated Post-Eruption Daily Flood Maxima.

Date	Observed Flow, cfs	Probability/ Return Period	Corrected[a] Best Estimate, cfs	Corrected[a] Worst Case, cfs
11/12/68	9,700	.120/1.14	12,800	14,700
01/21/72	26,800	.942/17.2	28,900	30,300
01/16/74	26,100	.923/13.0	28,800	30,400
12/04/75	25,900	.904/10.4	32,700	34,800
01/15/76	14,900	.630/2.7	19,800	20,700
12/02/77	29,400	.978/45.4	33,500	34,900
01/14/80	8,700	.060/1.06	15,000	16,900

[a] Adjusted by difference between recorded and simulated pre-eruption flows

Post-Eruption Flood Frequency Estimation - Toutle River

Estimates of the post-eruption flood frequency curve based on the 1968-1980 simulations is a less than precise analysis. Ideally, the model would have been run under post-eruption conditions for the entire 1930-80 period, and the 51 annual flood peaks identified under altered conditions. When the analysis is restricted to the shorter 1968-80 period, there is clearly no guarantee that the i'th largest flood under historic conditions will also be the i'th largest under post-eruption conditions. However, it is quite likely that the five largest historic events will also be the five largest post-eruption events (although their internal order may change) since there is a considerable difference in magnitude between the fifth and sixth largest historic events. If the post eruption magnitude of the December, 1933 event could be estimated, reasonable confidence could be placed on the ordering of the five largest events. A review of the historic record indicates that the December, 1934 flood was an unusually long event, with flow above flood stage for more than a week. Heavy rainfall resulting in flooding had also occured earlier in the month. Therefore, it is reasonable to assume that the post-eruption response change for this event, had it been modeled, would be similar to the January, 1972, and the 1974 floods. Accordingly, response ratios of 1.12 and 1.18 for the best estimate and worst case post-eruption conditions, respectively, were assigned to the 1933 event.

In addition to the largest floods, it was necessary to estimate post-eruption changes in lower recurrence interval events. This task was complicated because many of the moderate floods in the 1968-80 period were not well simulated. However, in years with large floods there are often lesser floods which are hydrologically similar to the annual maxima with low recurrence intervals in the annual flood distribution. Therefore, we attempted to select floods, whether or not they were annual maxima, corresponding to return periods in the range 2-5 years, which were well-simulated under pre-eruption conditions. The events selected (see Table 14) were November 12, 1968 (9700 cfs), January 15, 1976 (14,900 cfs), and January 13, 1980 (8700 cfs). The predicted post-eruption flood magnitudes for these events were ordered and plotted at probability levels estimated for the pre-eruption distribution of annual flood maxima. Although there is considerable uncertainty in the plotting position for these floods, since the rank of moderate floods is much more likely to be altered than for large floods, the results do allow an approximation of the recurrence interval of moderate floods. Insofar as the emphasis for planning purposes is on larger floods (i.e., return period 10 years) there appears to be little reason to attempt refinement of the estimation procedure.

The results of the analysis are plotted in Figure 23 on a log normal probability scale. The estimated post-eruption frequency curves emphasize the conclusions drawn earlier from a review of Figures 20-22, specifically the changes expected in moderate flood events are much larger than in extreme events. For instance, for the 2 year event the estimated increase in the daily flood maximum is 35% for the best estimate and 61% for the worst case, while for the 50 year event it is only 18% for the best estimate and 22% for the worst case. Essentially, then, the effects of the eruption on the watershed are predicted to be similar to those resulting from urbanization of a catchment; moderate storms result in greatly increased runoff, while extreme storms result in moderately increased runoff. Also, low flow is decreased, as infiltration is reduced.

Simulation Results - Cispus River

As noted earlier, simulation accuracy for the Cispus River was generally less than for the Toutle, since the meteorological data stations are more remote from this basin. Also, the Cispus was affected only by ashfall, and not by direct blast effects. Therefore, changes in flood response of this basin are expected to be much less than in the Toutle. Considering the modest changes in flood response expected, the effect of simulation errors, and uncertainty regarding ordering of post eruption annual flood volumes, estimation of a post-eruption flood frequency curve for this basin probably would not be useful. However, it may be instructive to review individual peak flows for selected storms which were well simulated using pre-eruption data.

The procedure used was identical to that followed for assessment of Toutle River response changes. Model parameter sets were selected to represent best estimates and worst case post-eruption condition. However, it should be emphasized that these parameter sets do not reflect estimates of post-eruption physical conditions _per_ _se_, rather they should be taken as alternative possible scenarios. Unlike the Toutle, where some identification could be made of specific impacts associated with areas of the basin, the effects of ashfall in the Cispus are not well defined, therefore it is very difficult to relate post-eruption conditions to model parameters. Fortunately, two considerations act to ameliorate the effects of this uncertainty. First, as noted above, the post-eruption changes are expected to be minor by comparison with the Toutle. Second, the runoff from the Cispus is regulated by Mossyrock Dam before reaching the populated areas of the lower Cowlitz basin, whereas the Toutle is unregulated.

The only parameter modified for the post-eruption runs was PCTIM, the fraction of impervious area. This was allowed to range from 0.004 for pre-eruption conditions to 0.05 for the best estimate and 0.15 for the worst case. Given uncertainty as to the hydrologic effects of the ash on surface detention and infiltration, no attempt was made to alter the subsurface storage zone volumes.

Results for selected storms which were well simulated under historic conditions are given in Table 15. Unfortunately, most of the extreme events of record were poorly simulated, and therefore are not suitable for post-eruption analysis. The one exception is the event of December 20, 1972 which corresponds roughly to the mean annual flood. The remaining events are of lesser magnitude and are exceeded, on average, several times each year. The fact that the events listed are of much lesser magnitude than those analyzed for the Toutle should be emphasized when comparing response ratios, which, as noted earlier in this chapter, tend to be higher for smaller events. Table 15 shows that the percent increase in peak runoff under the best estimate scenario ranges from 1.7 to 4.7 per cent, and for worst case conditions from 5.5 to 15.0 per cent. As expected, the higher per cent changes occur for storms early in the year with low antecendent precipitation.

Table 15. Selected Historic and Estimated Post-eruption Daily Flood Maxima.

Date	Observed Flow, cfs	Simulated Flow	Best Estimate	Per Cent Increase	Worst Case	Per Cent Increase
11/11/68	6600	5590	5820	4.0	6280	12.3
12/20/72	9850	9200	9620	4.5	10,532	14.4
12/20/79	4690	4480	4690	4.7	5160	15.0
02/16/70	3460	3380	3470	2.8	3770	13.6
06/04/70	3860	4080	4140	1.7	4300	5.5

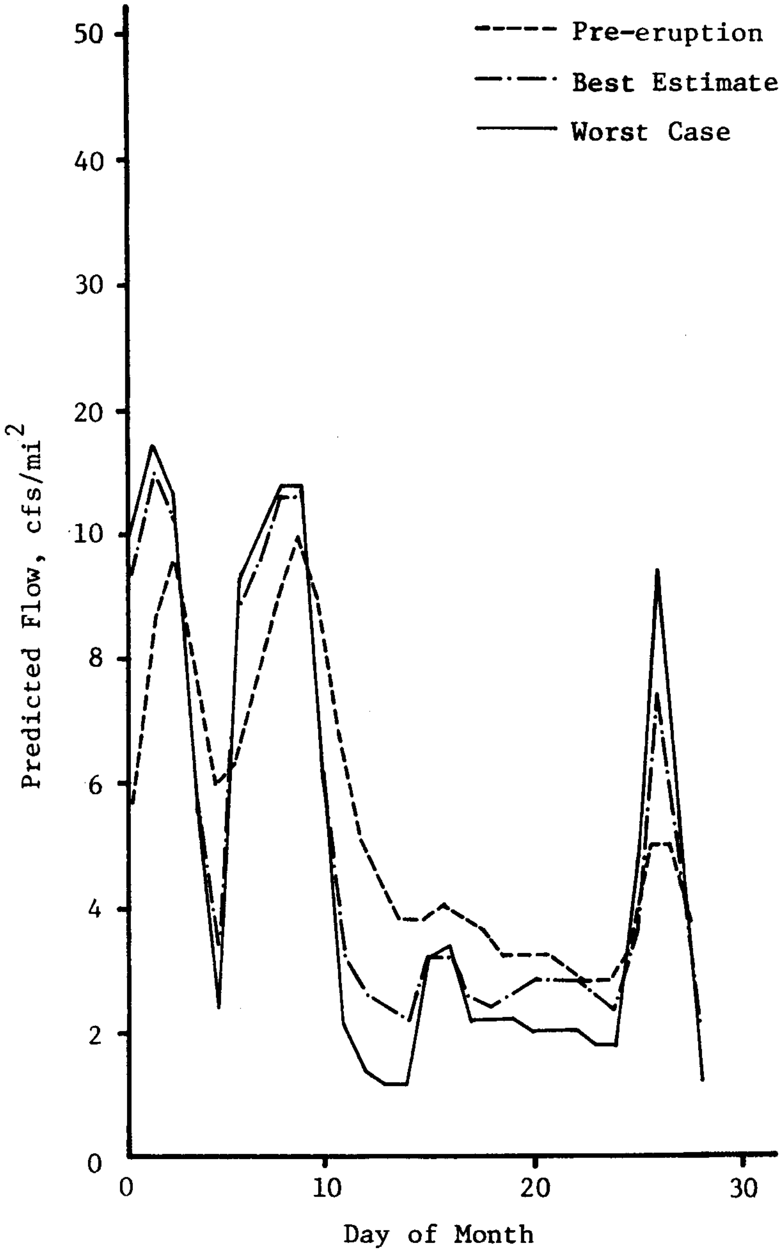


Figure 20. Simulated Runoff for February, 1978 for Toutle River near Silver Lake (USGS 14-2425) Under Pre-eruption, Best Estimate, and Worst Case Conditions.

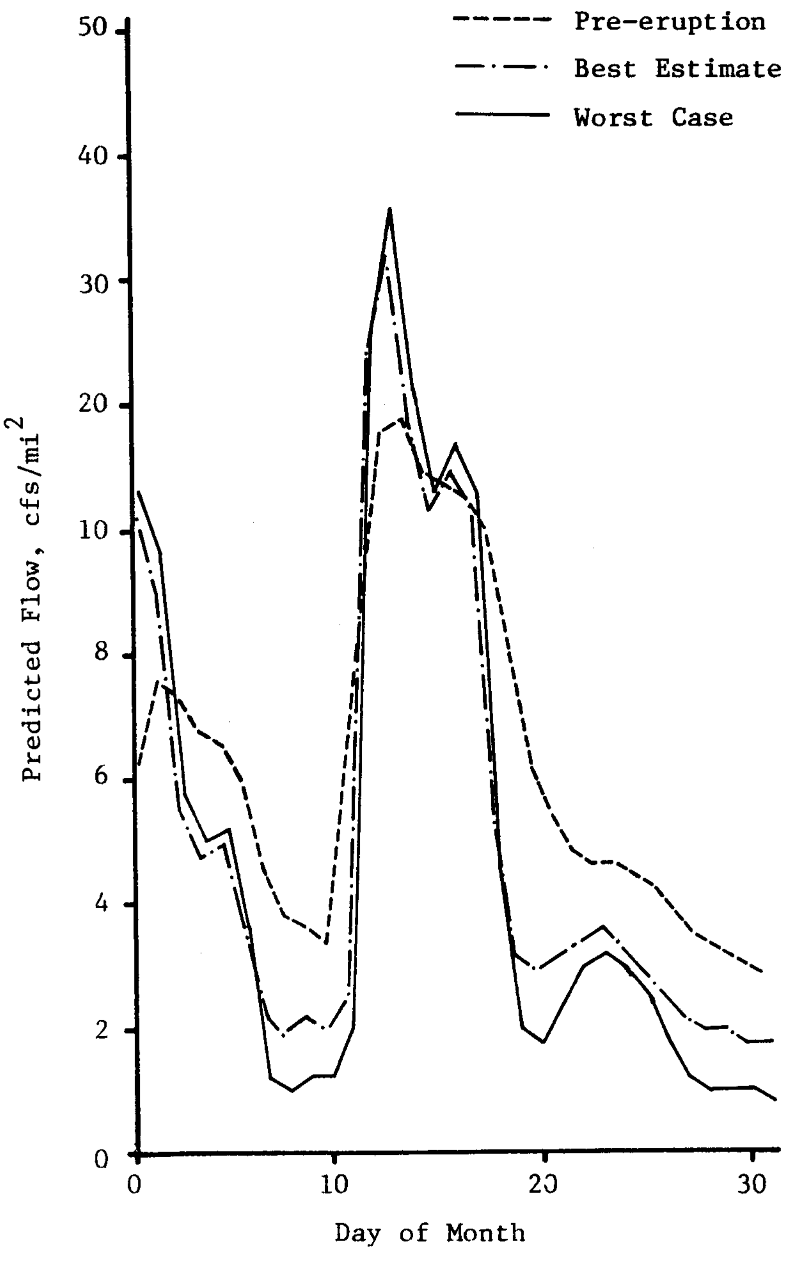


Figure 21. Simulated Runoff for January, 1980 for Toutle River near Silver Lake (USGS 14-2425) Under Pre-eruption, Best Estimate, and Worst Case Conditions.

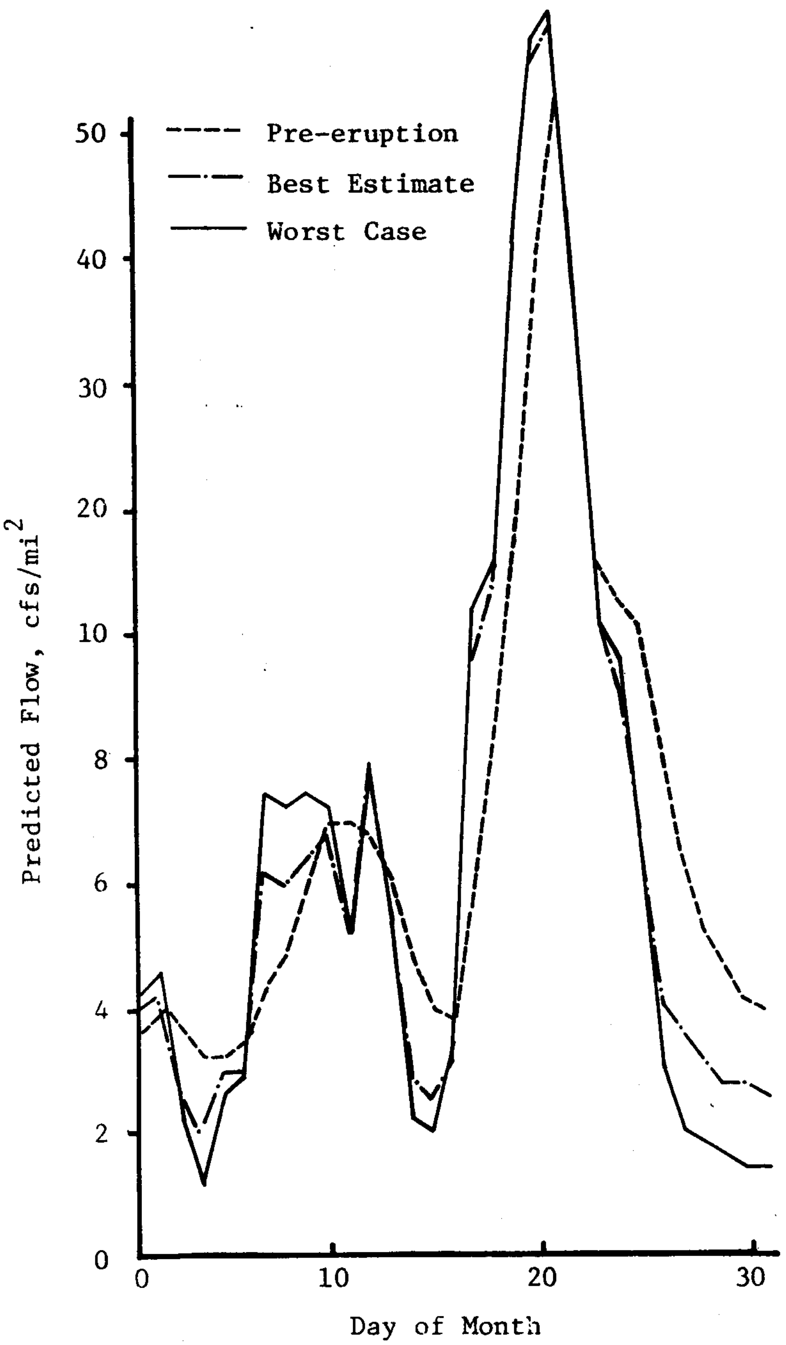


Figure 22. Simulated Runoff for January, 1972 for Toutle River near Silver Lake (USGS 14-2425) Under Pre-eruption, Best Estimate, and Worst Case Conditions.

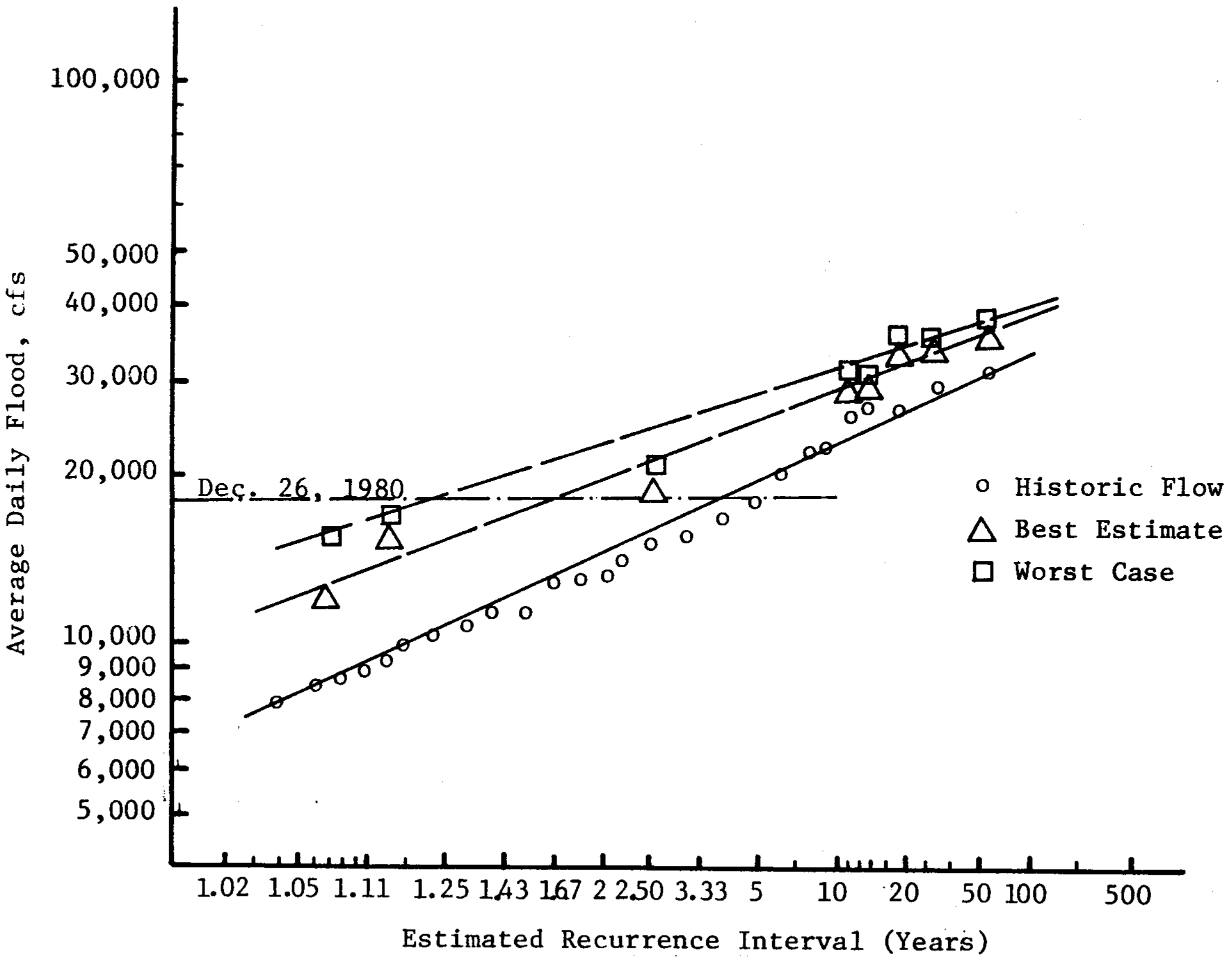


Figure 23. Estimated Flood Frequency Distribution for Toutle River near Silver Lake (USGS 14-2425) Under Pre-eruption, Best Estimate, and Worst Case Conditions.

CHAPTER VI.

SUMMARY AND CONCLUSIONS

The May 18, 1980 eruption of Mt. St. Helens resulted in substantial changes in the Toutle and Cowlitz River watersheds, as a result of changes in vegetation and alteration of land forms by the blast itself, effects of ash deposition on infiltration characteristics, and as a result of changes in the channel system. Two large mudflows in the North and South Forks of the Toutle River, which resulted in loss of much of the carrying capacity of the Cowlitz River channel in the vicinity of the towns of Castle Rock and Kelso and Longview, compounded the problem, raising concerns over the ability of the channel to contain even modest winter runoff events. Although dredging operations were initiated during summer, 1980 to restore the channel capacity to the greatest extent possible, the initial projected bankfull capacity of the Cowlitz at Castle Rock following completion of dredging operations was only about 75% of its pre-eruption value. Further, upstream hydrologic changes resulting in reduced infiltration capacity of the Toutle River watershed, and, to a lesser extent, the upper Cowlitz River watershed, suggested the possibility of increased runoff peaks and volumes. The work reported here was directed toward this latter concern.

Although some changes in hydrologic (rainfall-runoff) response of most tributaries to the Cowlitz River were expected, by far the most significant was the Toutle. In addition to its proximity to the mountain, the Toutle is unregulated by upstream storage, while the Cowlitz above its confluence with the Toutle is controlled by Mossyrock and Mayfield Dams. Operating policies for the reservoirs impounded by these dams were altered after the eruption to provide additional flood storage. Therefore, most of our attention was centered on prediction of post-eruption flood response of the Toutle River near its confluence with the Cowlitz.

The Toutle River, which drains an area of 474 mi^2 at the USGS gage near Silver Lake (the only long-term pre-eruption gage within the basin) is characterized by high annual mean precipitation, which varies by a factor of at least two over the basin's elevation range. At the highest elevations, most precipitation occurs as snow, while at the lower elevations snowfall is unusual, and when occurring usually does not persist for more than a few days. Most extreme flood events in this basin, as elsewhere in the Western Cascades, occur in December or January as a result of heavy precipitation accompanying a warm front, which results in rapid snowmelt. Therefore it was immediately apparent that any successful tool for predicting post-eruption flood runoff must model the accumulation and ablation of the snowpack. A cursory review of the data base indicated that the modeling effort must use low elevation precipitation and temperature records only, on a daily time scale.

The National Weather Service snow accumulation and ablation model was selected as a result of our familiarity with its structure and data requirements (not an insignificant consideration given the time constraints for completion of the project) and its compatibility with the available data. An elevation zone approach was used, with the basin divided into four areas of approximately equal size, subject to the elevation of the temperature stations selected. Much effort was directed toward establishing a data handling system compatible with the model. The system developed consisted of several preprocessing programs, which adjust precipitation and temperature to the median elevation of each elevation zone, and disaggregate daily values to a six hourly time step.

Attempts to calibrate the snowmelt model on the basis of available snow course water equivalent measurements were generally unsuccessful, owing to extreme spatial variability of snow coverage within each elevation zone. Consequently, the historic snow data were used only to verify that the predicted date of first snow accumulation in the fall and completion of melt in the spring were approximately correct; fine "tuning" of the model was based on calibration of observed and recorded runoff following implementation of the runoff model.

The runoff model used was the Sacramento version of the National Weather Service River Forecast System. This model operates on a daily time step, accounting for passage of incident moisture (rainfall on bare ground and snowmelt) through a soil moisture accounting mechanism, to its ultimate fate as runoff or evaporation. The model was selected based on our previous experience, and our judgment that the model can properly account for rainfall-runoff interactions in mountainous Northwest river basins.

The period including water years 1968-76 was used to calibrate the snowmelt and rainfall-runoff models, with verification from October 1976 through April 1980. Initial emphasis was placed on proper reproduction of annual runoff volumes, with subsequent adjustment of parameters to provide accurate reproduction of peak runoff from large floods. Insofar as four of the five largest floods in the 51 years of record for the Toutle River occurred during the calibration and verification periods, the pre-eruption simulation results gave reasonable confidence in the model's ability to predict extreme runoff events. The Toutle results were surprisingly accurate for large floods (errors generally less than 10%) for the largest floods considering the paucity of high elevation meteorological data. The results for the Cispus River basin, a tributary of the upper Cowlitz, were not nearly so accurate, however; this was attributable to the remoteness of the available precipitation stations from the basin.

Once the model had been calibrated to pre-eruption conditions, it was necessary to adjust model parameters to reflect post-eruption hydrologic changes. The ideal approach to accomplish this would be to recalibrate the model using post-eruption runoff data, however this approach was infeasible for two reasons. First, the interval between the eruption and completion of the analysis (June-October) was a period of low rainfall, therefore recorded flows were low and not at all characteristic of the extremes of interest. Second, the mudflows following the eruption resulted in destruction of the only pre-existing stream gage on the Toutle, and although quickly replaced by a temporary gage, rapidly changing channel cross-sections made the post eruption runoff record subject to much larger errors than the pre-eruption record. For these reasons, an alternate scenarios approach was elected wherein two sets of parameters representing a worst case and best estimate of present conditions was selected. The parameter sets representing each scenario were based on estimates of physical changes in post eruption conditions, particularly in the upper elevation zones of the Toutle river. These changes were primarily represented in altered infiltration and surface ponding characteristics. Using the altered parameter sets, the pre-eruption (1968-80) meteorological data were routed through the model, and predicted changes in runoff for the largest historic floods were noted. The predicted maximum annual events were then reordered, and augmented by predicted post-eruption runoff for more modest flood events. Two revised flood frequency distributions were estimated corresponding to the best estimate and worst case parameter sets.

The results indicated that the effect of the eruption on runoff should be analogous to urbanization of a watershed; runoff peaks and volumes increase, and the change is greater for moderate events. This is so because the effect of the eruption was to reduce infiltration capacity over much of the Toutle basin, and, to a lesser extent, the upper Cowlitz basin. However, during very large flood events, infiltration capacity has already been reduced by antecedent rainfall or snowmelt, and the change in runoff is comparatively reduced. In the case of the Toutle river, the predicted post-eruption increase in peak daily runoff ranged from 35% for the best estimated and 61% for the worst case at the 2 year recurrence interval, to 18% for the best estimate and 25% for the worst case at the 50 year recurrence interval. An additional post-eruption effect predicted was the reduction of low flows.

Although sufficient post-eruption data were not available at the time the work was completed to recalibrate the affected watersheds for post-eruption conditions, a post-eruption flood did occur on December 26, 1980. Under pre-eruption conditions, this would have been approximately a three year event, however our analysis indicates that under post-eruption conditions the recurrence interval for this event should have ranged from about 1.2 years (worst case) to 1.6 years (best estimate). Collection of additional post-eruption data should allow recalibration of the model, and the storm in question, as well as other extreme events yet to occur, will allow the basis for assessment of the accuracy of the prediction made herein. It is encouraging to note that no major damage occurred from the December 1980 storm, as regulation of flow on the main stem of the Cowlitz River was successful in holding peak flows in the lower Cowlitz below flood stage.

APPENDIX A: A GLOSSARY OF TERMS USED IN THE SACRAMENTO (NWS) STREAMFLOW SIMULATION MODEL

ADIMP - The additional fraction of impervious area which develops as tension water requirements are met.

ADIMC - The tension water content in inches for that portion of the basin defined by ADIMP.

ACTIM - The actively impervious fraction.

LZFPC - Lower Zone Free Water Primary Contents, the contents in inches of lower zone primary free water - the volume at a particular point in time, from which primary baseflow is being drawn.

LZFPM - Lower Zone Free Water Primary Maximum - the maximum capacity in inches of lower zone primary free water, i.e., the maximum capacity from which primary baseflow may be drawn.

LZFSC - Lower Zone Free water Supplemental Contents - the contents in inches of lower zone supplemental free water - the volume at a particular point in time from which supplemental baseflow is being drawn.

LZFSM - Lower Zone Free water Supplemental Maximum - the maximum capacity in inches of lower zone supplemental free water; i.e., the maximum capacity from which supplemental baseflow may be drawn.

LZPK - The fraction of LZFPC which is drained in one day.

LZSK - The fraction of LZFSC which is drained in one day.

LZTWC - Lower Zone Tension Water Contents - the volume in inches at a particular time contained by lower zone tension water storage.

LZTWM - Lower Zone Tension Water Maximum - the maximum capacity in inches of lower zone tension water.

PBASE - The maximum baseflow in inches per day when all lower zone free water storages are full, i.e., the maximum volume in inches which can be drained from lower zone free water storages. This value is the sum of the products of lower zone free water capacities and their drainage rates and is a governing factor in the percolation equation.

PCTIM - A decimal fraction expressing the minimum percent of the basin which is impervious and contributes to instantaneous runoff.

PCTPN - A decimal fraction multiplier, varying from month to month, to be applied to the loaded evapotranspiration demand in order to achieve a properly dimensioned evapotranspiration demand for the basin.

POTIM - The potentially impervious area, the sum of ADIMP and PCTIM.

PFREE - A decimal fraction expressing the percent of percolated water which is claimed directly by lower zone free water storages while lower zone tension water is loading.

RAWT - The rainfall weight which is applied to a particular station in computing the basin mean rainfall.

REXP - An exponent determining the rate of change of the percolation rate with changing lower zone water contents.

RSERV - The decimal fraction of lower zone free water which cannot be transferred to a deficient lower zone tension water.

SARVA - A decimal fraction representing that portion of the basin covered by streams, lakes and riparian vegetation.

SIDE - A decimal fraction defining the ratio of non-surface-draining lower zone free water to surface-draining lower zone free water, i.e., the ratio of non-channel baseflow to channel baseflow.

SSOUT - A discharge rate in CFS per square mile which must be provided to the stream bed before channel flow becomes visible at the surface discharge station. In many areas this term is so small that it can be set to zero, but under certain geological conditions it can assume a significant magnitude.

UZFWC - The quantity in storage as Upper Zone Free Water at any particular time. It is expressed in inches and represents the volume from which all water available for deep percolation and interflow drainage is drawn. See UZFWM.

UZFWM - Upper Zone Free Water Maximum, the limiting capacity of upper zone free water - the maximum volume which can be stored as Upper Zone Free Water Contents.

UZK - The fraction of UZFWC which is drained as interflow in one day.

UZTWC - Upper Zone Tension Water Contents, that volume in inches of soil moisture stored as upper zone tension water at any particular time. See UZTWM.

UZTWM - Upper Zone Tension Water Maximum, that volume of water in inches held by the upper layer between field capacity and the wilting point plus that volume below the wilting point which can be lost by direct evaporation from the soil surface. The maximum volume which can be stored as Upper Zone Tension Water Contents.

ZPERC - The additional multiple of PBASE which can be percolated when all lower layer storages are empty and upper zone free water storage is completely full.

REFERENCES

Anderson, E.A. "National Weather Service River Forecast System -- Snow Accumulation and Ablation Model," NOAA Technical Memorandum NWS Hydro-17, November 1973.

Burnash, R.J.C., R.L. Ferral and R.A. McGuire. "A Generalized Streamflow Simulation System -- Condeptual Modeling for Digital Computers," U.S. Dept. of Commerce, National WEather Service, Joint Federal-State River Forecast Center, Sacramento, CA, March 1973.

Kitanidis, P.K., and R.L. Bras, "Adaptive Filtering Through Detection of Isolated Transient Errors in Rainfall-Runoff models," Water Resources Research, Vol. 16, No. 4, pp. 740-748, August 1980.

Linsley R.K., M.A. Kohler and J.L.H. Paulhus. Hydrology for Engineers, Second Edition, McGraw-Hill, New York, 1975.

Peck, E.L. "Catchment Modeling and Initial Parameter Estimation for the National Weather Service River Forecast System," NOAA Technical Memorandum NWS Hydro-31, Office of Hydrology, Washington, D.C., June 1976.