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Department of Civil and Environmental Engineering

ASSESMENT OF CHANGES IN STORM AND SEASONAL RUNOFF RESPONSE OF WATERSHEDS IMPACTED BY MT. ST. HELENS ASH DEPOSITION

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Water Resources Series
Technical Report No. 82
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By

Bithin Datta

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and

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Water Resources Series

Technical Report No. 82

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Project Completion Report :	"Assessment of Changes in Storm and Seasonal Runoff Response of Watersheds Impacted by Mount St. Helens Ash Deposition"
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Principal Investigators:	Dennis P. Lettenmaier, Research Associate Professor, and Stephen J. Burges, Professor, Department of Civil Engineering, University of Washington

ABSTRACT

The most significant effects of the ash deposition following the major Mt. St. Helens eruptions during May to July 1980 were twofold. The immediate consequence of the ashfall was either to increase or decrease the runoff from snow-covered areas, depending upon the thickness of the ash cover. The thickness of ash deposits over some of the catchments in the vicinity of Mt. St. Helens were of the order of the most effective thickness for accelerating the ablation of a snowpack. This effect however, was short-lived and the changed rate of snowmelt returned to pre-eruption conditions by the end of water year 1980.

The second consequence of the ashfall was to change the hydrologic response of ash covered catchments to a given amount of precipitation. To study the changes in the hydrologic response of a catchment, it was necessary to model both the snowmelt process to determine effective precipitation, and the transformation of effective precipitation to runoff. Difficulties in calibrating existing snowmelt models due to large variations in topography and precipitation patterns led to rejection of classical approaches. As an alternative, it was decided to modify the Constrained Linear System (CLS) model in such a way that the physical characteristics of the catchments could be explicitly incorporated.

The Toutle River basin was one of the areas most severely impacted by massive mudflows, pyroclastic flows, and debris avalanche deposits. As a result the channel carrying capacity was significantly reduced and the catchment was affected by changes in vegetation cover and alterations of land forms. The ash deposits also reduced the infiltration capacity of the soil. Therefore, the Toutle River basin was chosen as the site for this investigation in Western Washington.

The modified CLS model was calibrated for the period October 1972 to September 1976 for the Toutle River on a daily time scale. This model was run in prediction mode for the period June 1980 to September 1982, which covers more than two years of the post-eruption period. An analysis of the prediction errors showed that the overall post-eruption hydrologic response of the catchment remained practically the same for the months from October to March while for other months, particularly June-September, the post-eruption runoff for given precipitation was less than under pre-eruption conditions. These results may be attributable to a post-eruption increase in ponding or depression storage capacity due to debris and blast deposits in the catchment.

Eastern Washington was also partly affected by heavy ashfall following the Mt. St. Helens eruptions. Existence of diversions and regulations in almost all the streams in the ash affected regions precluded considering them for this investigation. Crab Creek was chosen as a potential catchment because of absence of such diversions and regulations; however, efforts to model the precipitation - runoff process, were unsuccessful due to data limitations. Therefore, no conclusions could be drawn about the possible changes of hydrologic response in this area. Such changes are not, however, expected to be very significant due to the extensive agricultural use of the land and the extremely high evaporation demand compared to the precipitation.

ACKNOWLEDGEMENTS

The work upon which this report is based was supported in part by funds provided by the United States Department of the Interior, Office of Water Research and Technology, as authorized under the Water Research and Development Act of 1978. The Office of Water Research and Technology has since been terminated effective August 25, 1982, by Secretarial Order 3084 and its programs transferred to other bureaus and offices in the Department of the Interior. The Mt. St. Helens Research and Development Program was among those transferred to the Bureau of Reclamation.

Implementation of the NWS model for Crab Creek was performed by Mr. C. Gary Wolff, a former graduate student in the Department of Civil Engineering, University of Washington. Assistance provided by Ms. Karol Erickson in the initial stages of data manipulation is appreciated. The authors are thankful to Mr. Keith Loague, presently a graduate student at the University of British Columbia, for refining the computer code of the modified CLS model. Assistance provided by Mr. Rod Williams of the U.S. Geological Survey, in updating some of the hydrologic data is also appreciated.

DISCLAIMER

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CHAPTER I

INTRODUCTION

The eruptive activity of Mt. St. Helens during the period March 29 to July 29, 1980, including the spectacular explosive eruption on May 18 which removed approximately 1000 ft. of the peak dome, had three distinct effects. First, the direct blast resulted in the transport of mud, molten material and debris flows, as well as ashfall. Second, the pyroclastic flows resulted in morphologic and fluvial morphologic changes in the catchments and streams; from a hydrologic standpoint the pyroclastic flows primarily affected channel routing characteristics and ponding (interception and depression storages). Finally, ash deposition, depending on the quantity deposited, altered the infiltration characteristics of a number of catchments, hence, the hydrologic response to precipitation. This study deals with the effects of ash depostion only; earlier work by Dunne and Leopold (1981) and Lettenmaier and Burges (1981) has dealt with the first two hydrologic impacts. It must, however, be emphasized that all of these impacts are related and almost inseparable if the goal is to evaluate the resulting flood hazard or frequencies rather than the rate of runoff caused by a given amount of precipitation occurring under specific conditions (Dunne and Leopold, 1981). Nonetheless, outside the Toutle River basin and certain portions of Upper Lewis River basin, effects of the eruption were confined to ashfall (Figure 1).

Immediate Impacts of the Eruption

The main impacts of the ash deposition were two-fold. The short-lived consequence of the ashfall on the snowpack was either to increase or decrease the rate of snowmelt, depending upon the thickness of ash (Brown, 1982;

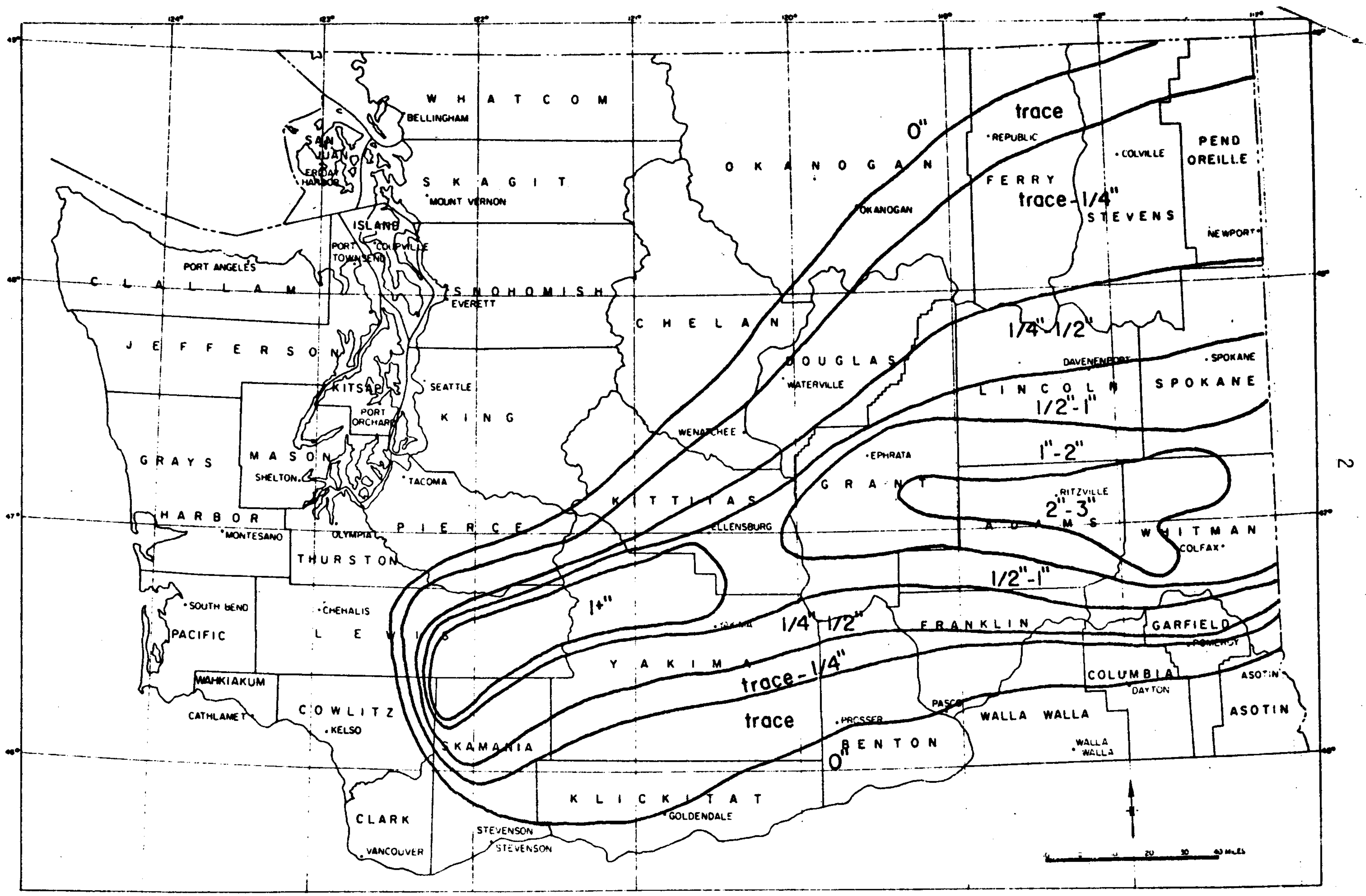

Figure 1. Ash Thickness Distribution of the May 18, 1980 Mt. St. Helens Eruption

Driedger, 1981; Tangborn and Lettenmaier, 1981). As reported in Brown (1982), an ash layer of 0.003 m. may be the most effective thickness for accelerating the ablation of a snowpack. Thinner layers do not absorb the optimum amount of solar radiation, while thicker layers act as insulation. The thickness of ash deposits over some of the catchments in the vicinity of Mt. St. Helens were of this order. This may have caused temporary increases in the snowmelt rate compared to the pre-eruption conditions, for a given degree day. This effect is, however, short-lived and the increase in snowmelt amount decreases with the gradual removal of the ash cover.

Tangborn and Lettenmaier (1981) found that the Nisqually River basin demonstrated the greatest hydrologic influence of ash deposition on snow. These effects were less apparent for the American, Cowlitz, and Cispus River basins, most likely because these lower altitude catchments contained less snow. However, there is some evidence that the larger deposition of ash in these basins had an insulating effect which retarded melt in the months following the May 18 eruption. It was also noted that incoming solar radiation strongly influences the effect that a decreased albedo will have on melt rates, and the above average cloudiness in the Pacific Northwest following the May 18 eruption caused the hydrologic effect of ash deposition to be less severe than if clear skies had predominated in the post eruption period. It was concluded that changes in runoff response due to the immediate effects of ashfall on snowpack were subtle, which appears to be the result of cloudy conditions following the eruption, and below average snowpack.

The other effect of the ashfall is changed basin response to a given amount of precipitation. Runoff is related, in addition to precipitation, to baseflow occuring as recession from groundwater storage, which is fed by infiltration from previous storms. Infiltration is dependent, in turn, on the permeability of the soil. Following the eruption and the ashfall, a major portion of the catchment areas within the blast zone were covered by ash, which consisted of very fine, almost cement-like impermeable material. Most river basins in Western Washington are covered by dense forest which aids in the interception of major portions of the precipitation. Therefore, prior to the eruption, "almost all storm runoff was generated by slow subsurface flow and by quicker runoff over the surface of restricted areas of saturated soils in swales, on footslopes, and on valley floors. Where ash fell into thick, undisturbed forest litter and understory plants in standing timber (even where trees were killed or damaged by the volcanic blast) the high infiltration capacity of the soil seems to have been preserved" (Dunne and Leopold, 1981). However, in places where the blast deposits of ashfall cover continuous clearcut or devasted areas, the infiltration capacity may be much lower than that existing before May 18, 1980.

As is evident from the ash thickness distribution maps provided by the Washington State Department of Natural Resources (Figures 1, 2, and 3), the ash-fall thickness exceeded one inch in very limited areas. It was as thick as two to three inches only in some parts of Eastern Washington, following the major eruption of May 18, 1980.

Other effects of the eruptions may be summarized as:

1) increased rates of snowmelt due to the removal of the forest cover, due to higher exposure to energy fluxes;
2) higher erosion rates in the bare, mechanically weak sediment of the debris avalanche, mudflow, blast and airfall deposits;
3) changes in the channel configuration resulting in increased flood hazard for identical amounts of streamflow before and after the eruptions; and

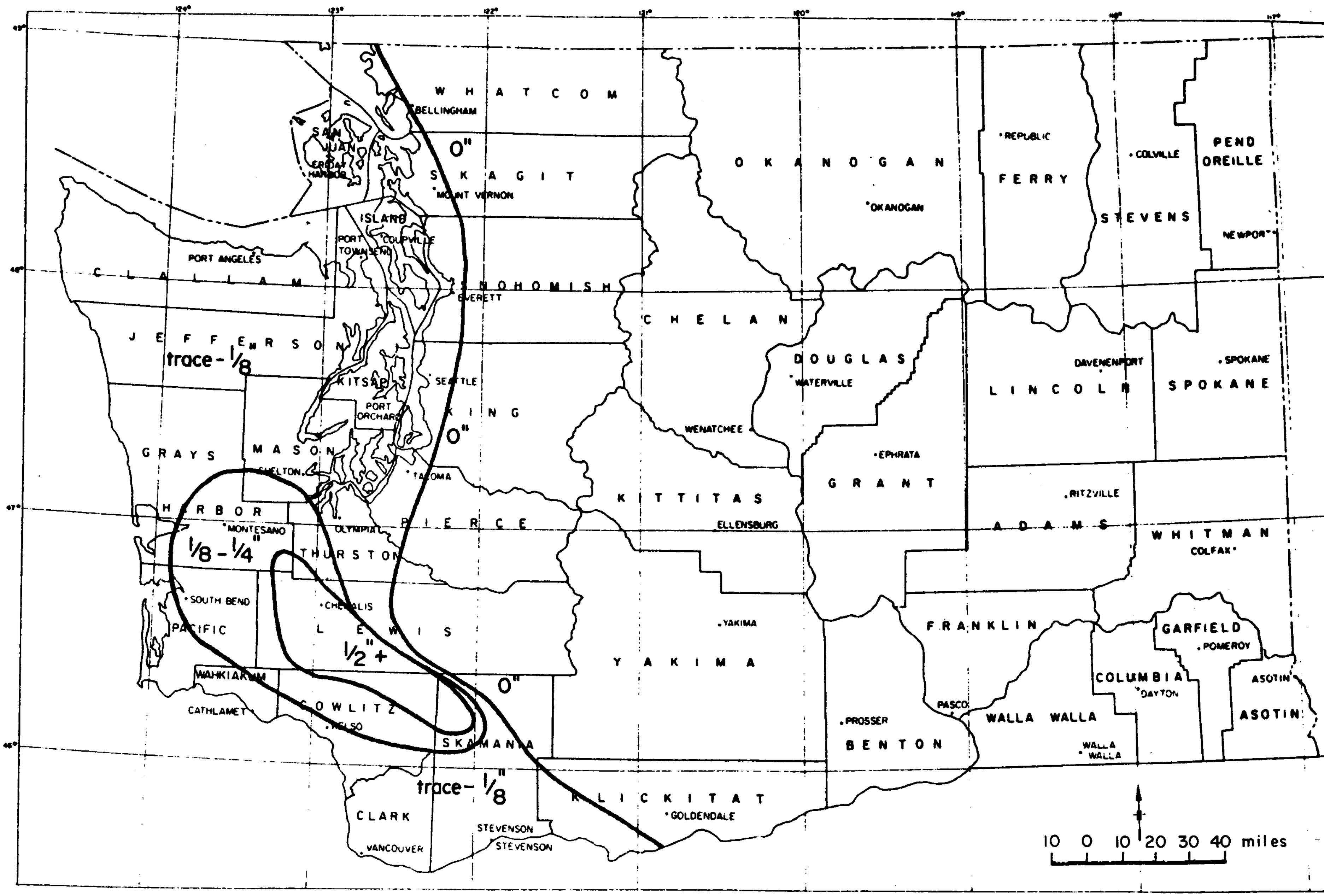

Figure 2. Ash Thickness Distribution of the June 5, 1980, Mt. St. Helens Eruption

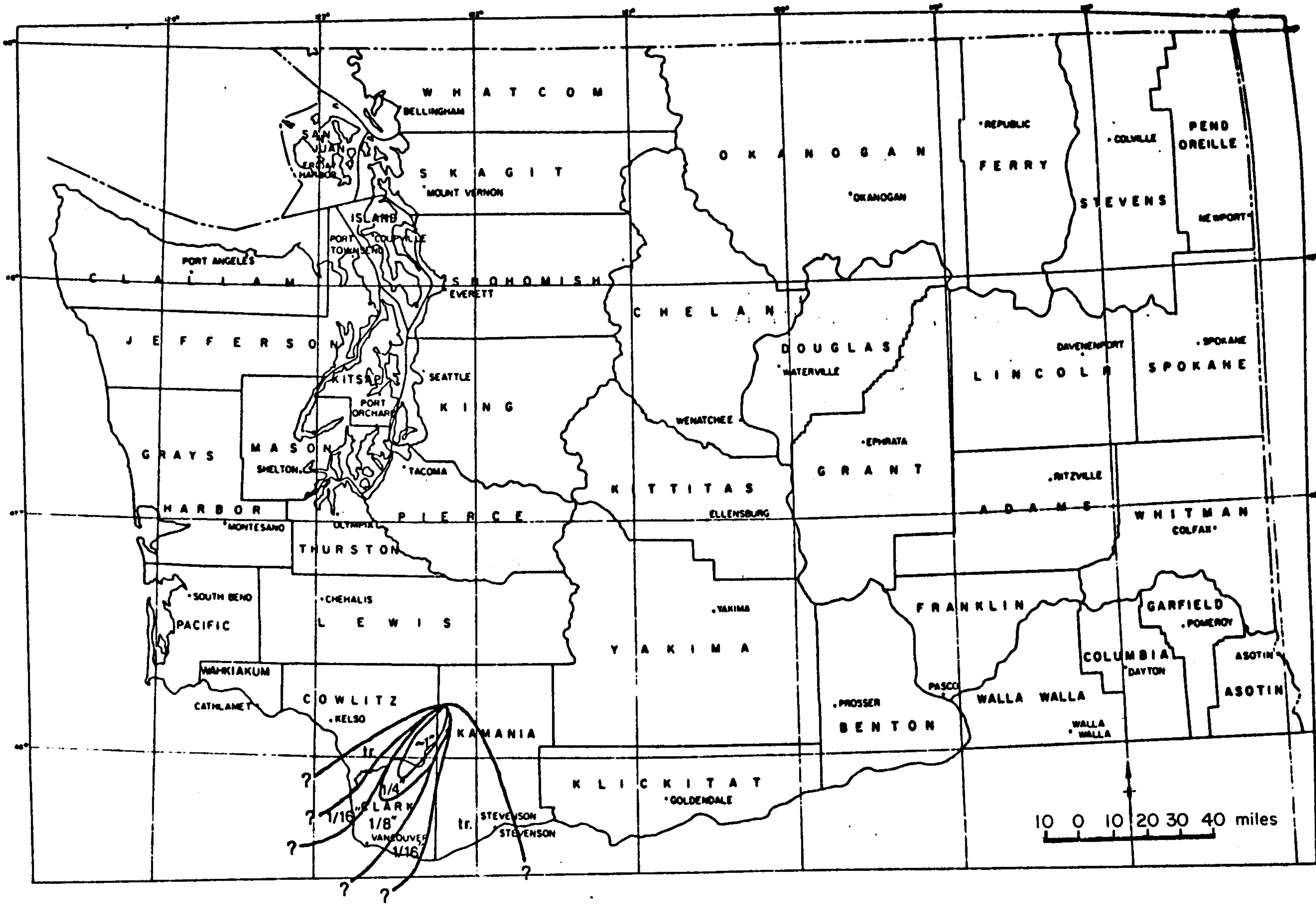

Figure 3. Ash Thickness Distribution of the June 12, 1980, Mt. St. Helens Eruption

4) accumulation of water and sediment from surrounding hill slopes, in lakes formed as a result of impounding by debris avalanches. These temporary lake-like formations significantly increase ponding in the catchment, thus substantially counterbalancing the effects of decreased infiltration rates.

The geomorphologic changes in the catchments affected by the ash fallout and blast deposits are important in determining the increased flood hazard especially in the Toutle and Cowlitz Rivers (Lettenmaier and Burges, 1981). While the ash deposits have the principal effect of changing the response of the catchment to incident precipitation (rain and snowmelt), the primary effects of pyroclastic flow deposits and blast deposits are primarily changes in the geometry of the stream channels and their carrying capacity. Therefore, even if the response of the catchment to a given amount of precipitation remains unchanged due to the overall integrated effects of different constitutive changes, the hazards of flooding or increase in river stages caused by the same amount of discharge are still possible under post-eruption conditions. However, the latter aspect is not addressed here, as it was the subject of a separate study (Lettenmaier and Burges, 1981).

Scope of this Study

In this report only one aspect of the eruption effects is considered, i.e. changes in response of selected catchments to precipitation. One of the main problems of assessing response changes is the availability of data and its reliability. Therefore, any conclusions that can be drawn are based on reasonable assumptions of reliability of the data. Also, the conclusions are limited by data sparsity. This problem is further complicated by the fact that in the region of study, the gross precipitation is a combination of rain and snowmelt. Although reasonably accurate point records of low elevation rainfall are available, the range of elevations in the catchments in the vicinity of Mt. St. Helens results in significant spatial variability of the rainfall, which can at best be incorporated in a lumped manner. For estimating the snowmelt, the difficulties are much more pronounced. In practice, snowmelt models must be calibrated indirectly via comparison of the output of a soil moisture accounting model with recorded runoff. This process of calibration can only resolve major systematic errors in the snowmelt model parameters; however, in the absence of extensive snow water equivalent records which are not available, this is the only option.

Keeping in mind the above limitations, it was decided that the best method of assessing changes in response of the catchments was to model the precipitation runoff process for the pre-eruption conditions, then use the same model(s) to predict the post-eruption conditions and detect the plausible changes. For this purpose two different catchments were selected; one in Western Washington in the immediate vicinity of the eruption and the other in Eastern Washington in the area of maximum ashfall. These two catchments differ considerably in physical characteristics. The total annual precipitation in the area of Eastern Washington of interest is on the order of ten inches, and the potential annual evaporation demand is on the order of 50 inches. The main consequence of the eruption in Eastern Washington was the ashfall alone, while in the immediate vicinity of the eruption, the major effects were debris avalanches, mudflows, pyroclastic flows, and blast deposits as well as ashfall. The mean annual rainfall in Western Washington is 6 to 12 times higher than that in Eastern Washington and is highly dependent on elevation, whereas elevation variations are much less significant in most Eastern Washington catchments.

The Toutle River was chosen as the demonstration basin in Western Washington because this catchment experienced the greatest changes (Figure 4) following the Mt. St. Helens eruptions. Crab Creek was selected as the Eastern Washington demonstration basin for two reasons. The Crab Creek catchment was heavily effected by ashfall following the May 18, 1980 eruption, and in general the ash deposition exceeded one inch over the entire catchment area (Figure 4). Also the runoff records for this drainage were among the very few available in the ash affected zone without significant diversions for irrigation purposes. This factor was essential for evaluation or implementation of any precipitation-runoff model. However, as this report will discuss later, the low amount of precipitation and extreme evaporation demand in this area make it difficult or impossible to adapt or calibrate any model for this region.

Selection of the Model

Initially, the National Weather Service River Forecast System models were implemented for the Toutle River (Lettenmaier and Burges, 1981). This system consists of the snow accumulation and ablation model of Anderson (1973) and the soil moisture accounting model of Burnash et al. (1973). These two models were used separately, with the output from the snow model forming the input to the soil moisture accounting (runoff) model. However, the snow model uses a six-hour time step (which is essential to allow distinction of snow and rain events), while the runoff model operates on a daily time step. Therefore, the outputs from the snow model were aggregated to daily events.

For the Toutle River, the runoff gauging station was USGS No. 14-2425, near Silver Lake (Figure 5). This gauging station accounts for approximately 474 square miles of the approximately 512 square miles of the Toutle River

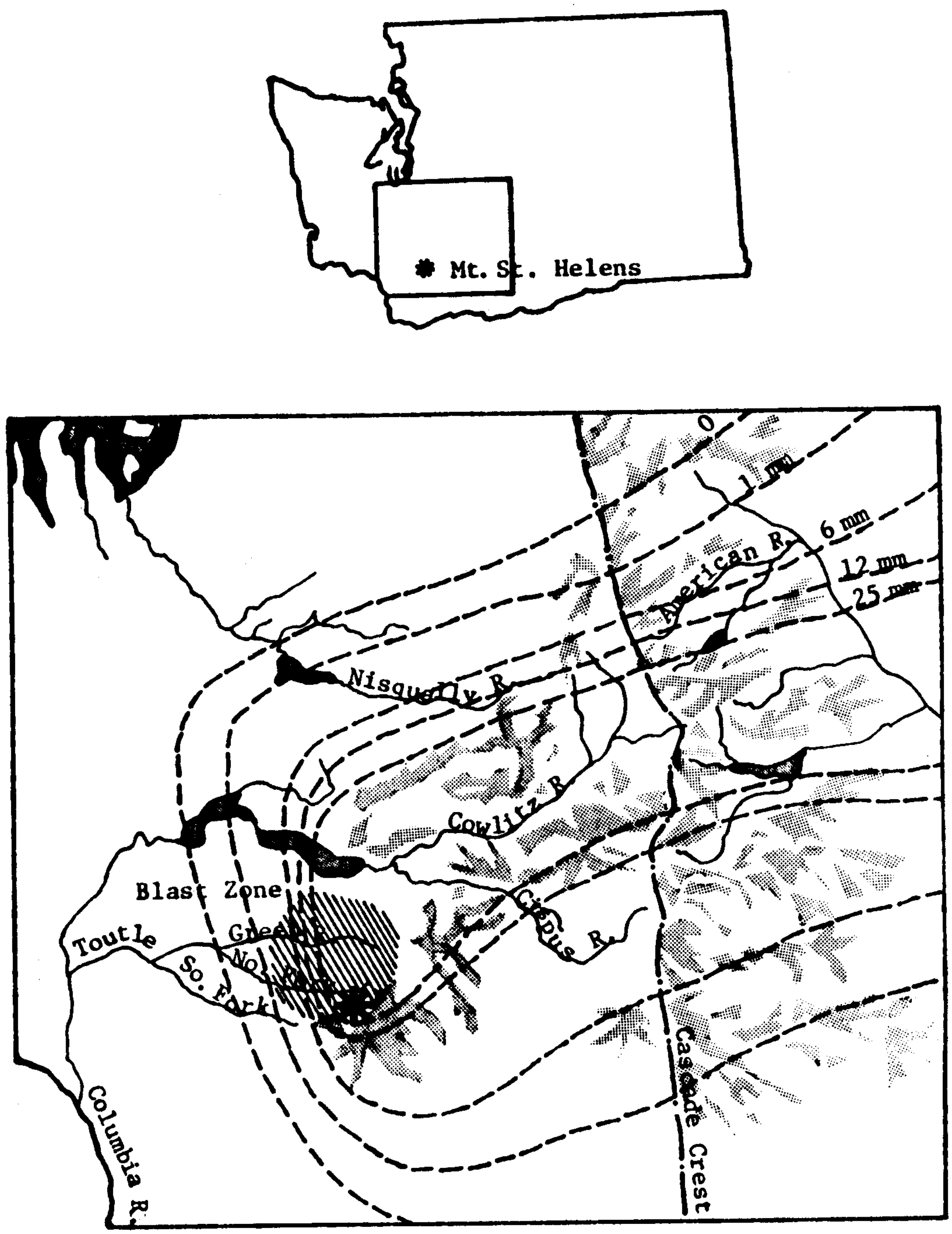

Figure 4. River Basins with Boundaries of Blast Zone and Ash Deposition Profiles from May 18 Eruption

drainage area. The catchment varies in elevation from about 400 to 5,000 feet. The range in elevation results in significant spatial variation in temperature and precipitation; therefore, it was decided to subdivide the entire basin area into elevation zones. Temperature and precipitation recording stations at Kid Valley, Glenoma, Cougar, Longmire, and Paradise were selected as representative of the elevation zones, after interpolation to represent the mean elevation. It is important to subdivide the area into different elevation zones, especially because low elevations usually receive rain while higher elevations receive snow from the same storm. Table 1 gives the basin characteristics for the Toutle River basin and Figure 5 shows the Toutle River basin.

Table 1. Pre-Eruption Basin Characteristics for the Toutle River Basin (from U.S. Geoological Survey Basin Characteristics File)

	Toutle River (above USGS 14-2425)
Drainage area, mi^2	474
Mean basin elevation, ft	2,310
Mean annual precipitation, inches	84
Mean channel slope, ft/mile	78
Stream length, miles	44
Forested area, percent	94

The spatial variation of ground elevation in the Crab Creek catchment is negligible, while the contributing area of the catchment to the discharge gauging point at Irby (USGS No. 12-4650) is 1,042 square miles. Only two precipitation and temperature recording stations were available: Odessa and Harrington.

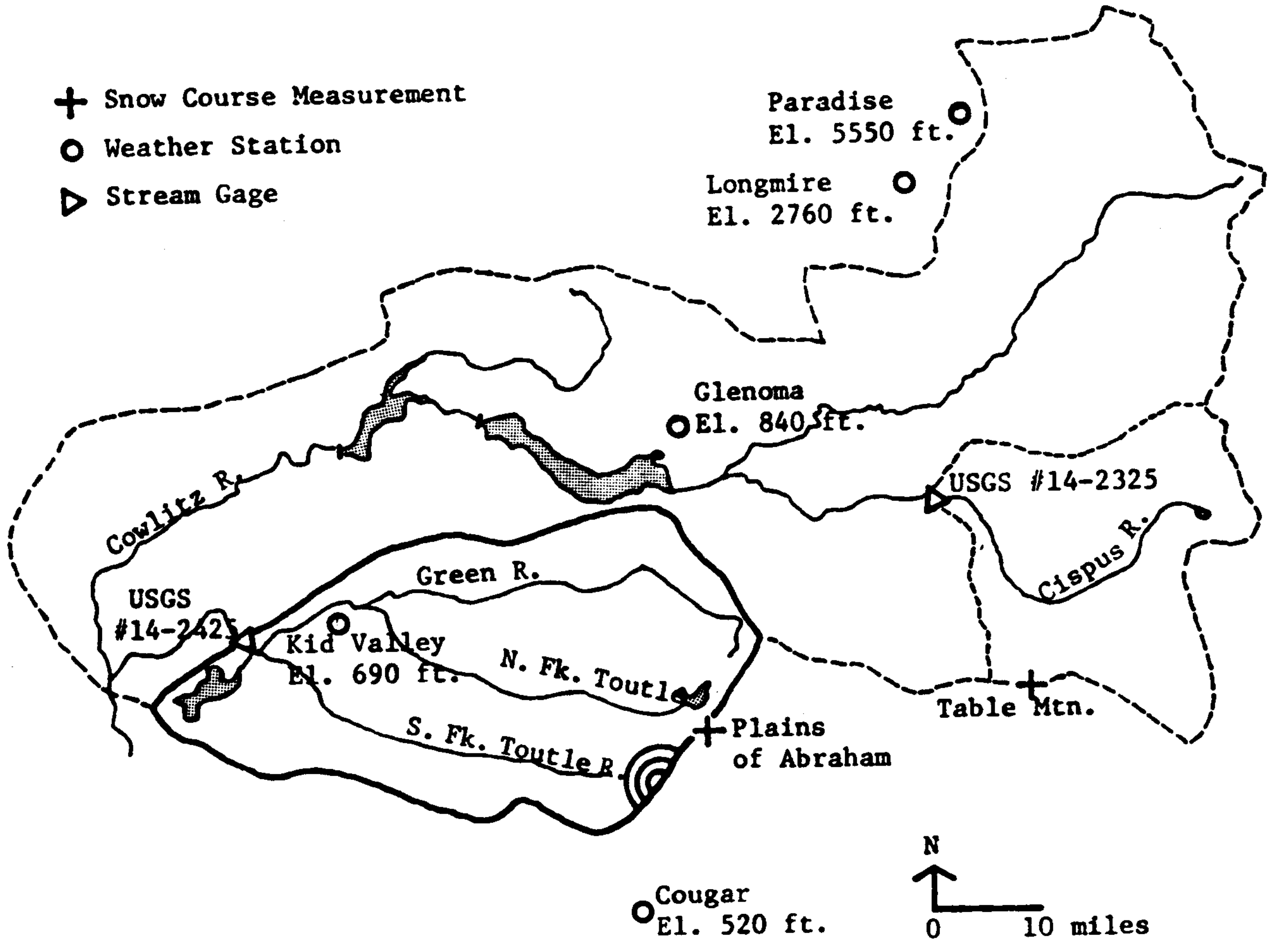

Figure 5. Cowlitz and the Toutle River Basins with Key Stream Gages, Metereological Stations and Snow Courses

For the purpose of modeling the precipitation runoff process of Crab Creek, it was assumed adequate to consider only a single elevation zone. However, two elevation zones were also used. The results did not differ appreciably. It was found that the precipitation records at Odessa were most compatible with the runoff records, so only one station was used for the temperature and precipitation records.

As described earlier, the National Weather Service River Forecast System models were initially implemented for both catchments. For the Toutle River, a generally satisfactory calibration was achieved. However, the model failed to simulate the recession part of the hydrographs. Also, for some months like September, when a series of high flows occurred following a long dry spell, the simulated hydrographs showed peak flows much in excess of the recorded flow. Additional complications occurred in calibration of the snowmelt model. The input to the runoff forecasting model is combined rain and snowmelt. Snowmelt can only be estimated by using Anderson's (1973) snow accumulation and ablation model. However, this model cannot be directly calibrated in the absence of extensive snow course data. In addition, the number of parameters that must be estimated in the NWS soil moisture accounting model is large, and some of the parameters are interrelated. Again, the problem of subdividing the basin into a number of sub-basins requires that the model be used separately for each sub-basin and that the outputs be lumped together to obtain the total runoff at the gauging site.

To overcome these limitations of the NWS River Forecast System models, and in particular, the soil moisture accounting (runoff) part of the model, it was decided to use a black box type of approach to runoff modeling. This approach requires substantially fewer parameters and can rectify systematic errors in the input data. It has the further advantage that it is selfcalibrating. Development of this model will be discussed in Chapter 2.

The model used for the Toutle River was a modified version of the Constrained Linear System (CLS) model (Todini and Wallis, 1977). Major modifications were made to this model to incorporate physical characteristics of the catchments. These physical characteristics were necessary to determine the effective precipitation (rain and snowmelt) which was then used as an input to the original CLS model. This method removes the total black box approach in the original CLS model and was found to be better suited to the simulation and prediction runoff volumes on short time steps. The NWS snow accumulation and ablation model was still used to estimate the total amount of pseudo precipitation. For Crab Creek, the NWS River Forecast System models and also the modified CLS model were both attempted with limited success, the reasons for which will be discussed in Chapter 5.

Method of Analysis

Once the runoff models were satisfactorily calibrated, the statistical characteristics of the simulation errors were evaluated. Of interest were the statistical properties of these errors for pre- and post-eruption conditions, using simulations based on model parameters for pre-eruption conditions; observed trends in the errors will be analyzed in Chapter VI of this report. Attempts to carry out this type of analysis for Eastern Washington were unfortunately unsuccessful. However, it may be assumed that due to extensive agricultural use in many of the catchments affected by ashfall, the top layer of the soil may have been upturned, preventing the cement-like ash deposits from forming an impermeable surface. Therefore, the temporary changes in response of these catchments may be short-lived and negligible in the long run.

CHAPTER II

DEVELOPMENT OF A PRECIPITATION-RUNOFF MODEL

The transformation of rainfall to runoff is a complex physical phenomenon, the physical aspects of which are yet to be fully understood. Ideally, a conceptual model based on sound physical principles would be the best approach to modeling the rainfall-runoff process. However, in practice, the complexities of natural catchments, together with the limitations imposed by computational feasiblity, budget and data availability dictate the adoption of models based on simplifying assumptions and empirical laws. Particularly when dealing with discrete time rainfall-runoff modeling of watersheds, it is possible to simplify considerably and approximate the details of the actual physical process, and still develop a fairly good model to describe the process. Development of such a model, which approximately accounts for the physical characteristics of the catchment and then uses a black box type approach to estimate a transfer function between the computed net precipitation and the observed runoff, is discussed in this chapter.

The model developed uses a preprocessing unit to compute the net precipitation input from gross pseudo precipitation (rain and snowmelt) by accounting for the interception and depression storage, interflow, and infiltration. The Constrained Linear System model (Todini and Wallis, 1977) is then used to transform the preprocessed precipitation into predicted runoff. This transfer function, together with the preprocessing unit of the model, may be synergistically used to predict future runoff volumes from the raw precipitation data.

The above modifications account for the physical characteristics of the catchments, which are not included in the CLS model. Addition of these parameters to the original model is also very helpful in detecting the change of hydrologic responses of the catchments for post-eruption conditions, based on physical explanations.

Background for Model Development

The types of models developed in the past to describe the rainfall-runoff process may be broadly classified into two distinct categories. The first is the black box approach in which the rainfall and runoff are depicted as inputs and outputs, respectively, to a black box. A transfer function is then obtained to simulate the outputs, given the inputs. Once the parameters of the transfer functions have been calibrated to the satisfaction of the modeler, these parameters are utilized in predicting future outputs for given inputs. Models in the second category attempt to base the rainfall-runoff relationship on mathematical statements of the laws of physics. However, as pointed out by Todini and Wallis (1977), "the physics-based model uses large amounts of computer data and, to be operational, needs almost limitless time, or the introduction of other approximations that tend to pollute the elegant purity of the model. For discrete time rainfall-runoff modeling of whole watersheds over long time spans we must leave the sublime world of physics-based models and enter the realities of gross empirical models that use lumped parameters and arbitrary assumptions about watershed response and geometry."

The instantaneous unit hydrograph method, or the use of time series methods for simulating runoffs from rainfall data by using suitable transfer functions are, strictly speaking, black box types of approaches, though they can be linked to the solution of the St. Venant's equations under simplifying assumptions (Natale and Todini, 1977). The instantaneous unit hydrograph method

(IUH) assumes a time invariant impulse response for a given catchment and is also based on a principle of superposition or linearity. In the traditional methods of using this concept, "IUH techniques do not seem capable of being refined beyond a stage where the hydrograph is separated into two components (runoff and baseflow) and nonlinearity in the process is accounted for by replacing rainfall with 'effective' rainfall depending on some antecedent precipitation index." (Kitanidis and Bras, 1978).

The time series approach is severely limited in its scope due to time variance, non-stationarity and nonlinearity in the rainfall-runoff process, all of which are difficult to incorporate in the model. Some of the severe limitations of conceptual models due to large data requirements and estimation of numerous parameters were partially relaxed in the models developed by Kitanidis and Bras (1978). They used a simplified state space formulation of a conceptual hydrologic model, where the state of the system was represented as a random vector. This approach is useful for incorporating the various forms of model uncertainties and using a continuous correction scheme (filter) with feedback information. It is particularly suitable for real time, short lead time forecasting of runoff volumes.

The concept of a time invariant linear system with constraints placed on the parameters to be estimated was utilized in the Constrained Linear System (CLS) model proposed by Natale and Todini (1977). A further modification of this method was made by Todini and Wallis (1977) to account for a time variant nonlinear system. This was accomplished by introducing multiple impulse responses for the catchment based on an antecedent precipitation index. Extensive testing of this model for simulating the daily rainfall-runoff relationships for the Toutle River in Western Washington was performed by the authors with unsatisfactory results. The CLS model as originally proposed, invariably failed to simulate the recession part of the hydrograph when the precipitation input approached zero (see Figures 6a and 6b). Also, for certain months like September, when a couple of days of high precipitation can occur after a long dry spell, the simulated runoff was extraordinarily high (300 to 400 percent positive error) compared to the observed runoff (Figure 6c). It was not possible to adjust these errors in the calibration process even by introducing as many as three impulse responses.

This method of obtaining multiple responses to input vectors in CLS is based on splitting the precipitation inputs into more than one group, depending upon the antecedent precipitation index (API). Conceptually, the CLS model thresholds can be thought of as an antecedent moisture condition. When the total precipitation in a prior counting period, L, is greater than a threshold, T, the present precipitation plus that of M preceeding periods are put into a separate input vector and removed from the first vector. It was reported by Todini and Wallis (1977) that "... many combinations of L and M yield seemingly similar solutions. However, CLS is responsive to the threshold value and if little precipitation is moved then the extreme peaks are fitted well but average error variance does not decrease appreciably."

One of the drawbacks of this approach is that it does not consider soil moisture conditions, except indirectly through API. Although there has been discussion about the validity of using the API as an index for the effect of antecedent conditions on runoff (Linsley et al., 1975); there have been few reported attempts to establish a relationship between the API and such physical measures as soil moisture content. In addition, the API criterion does not distinguish the depression or interception storage contributions from the gross input precipitation.

To evaluate the change of response of a catchment after an intervention,

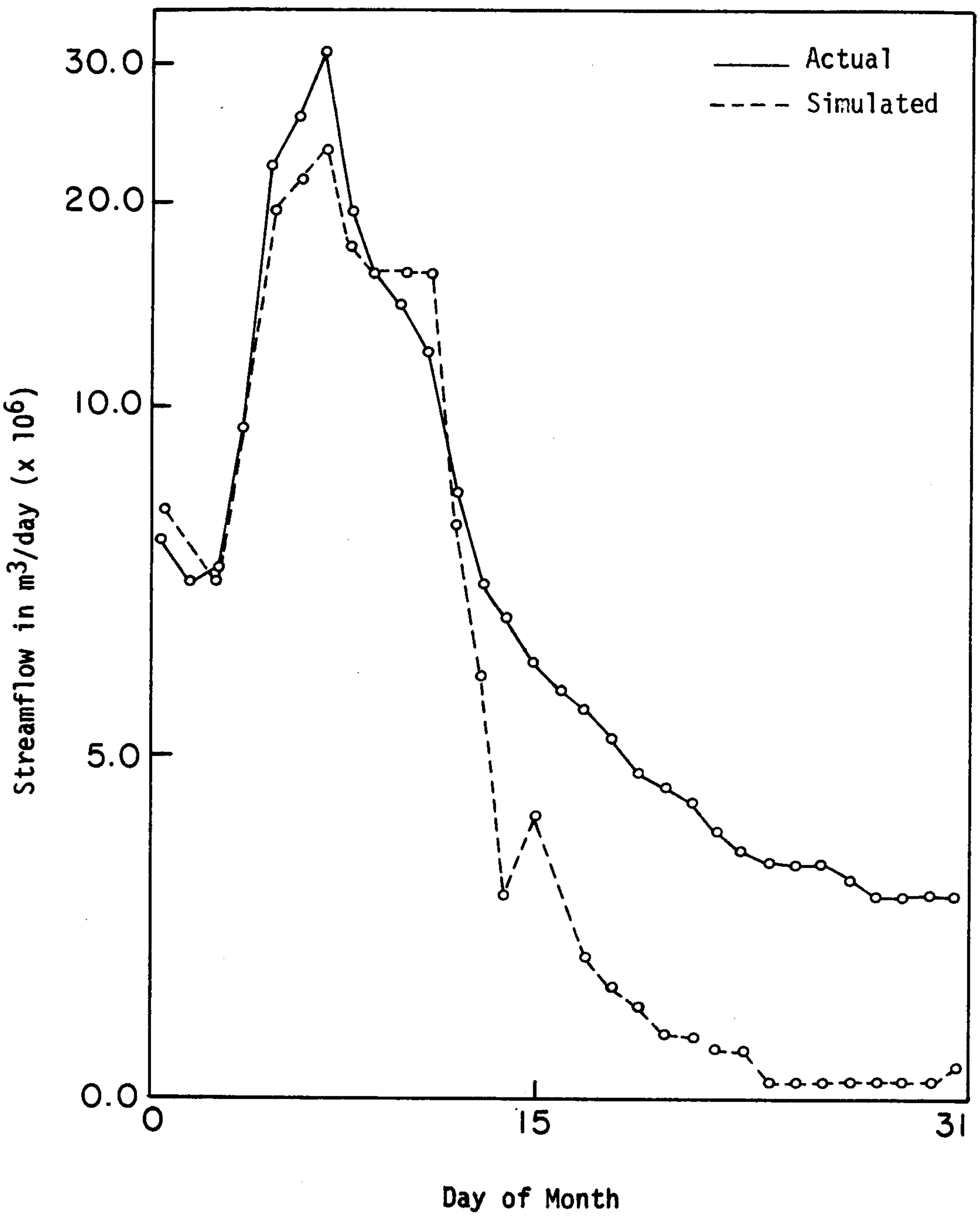

Figure 6a. Observed and Simulated Flows for the Toutle River Using Original CLS Model, January, 1979

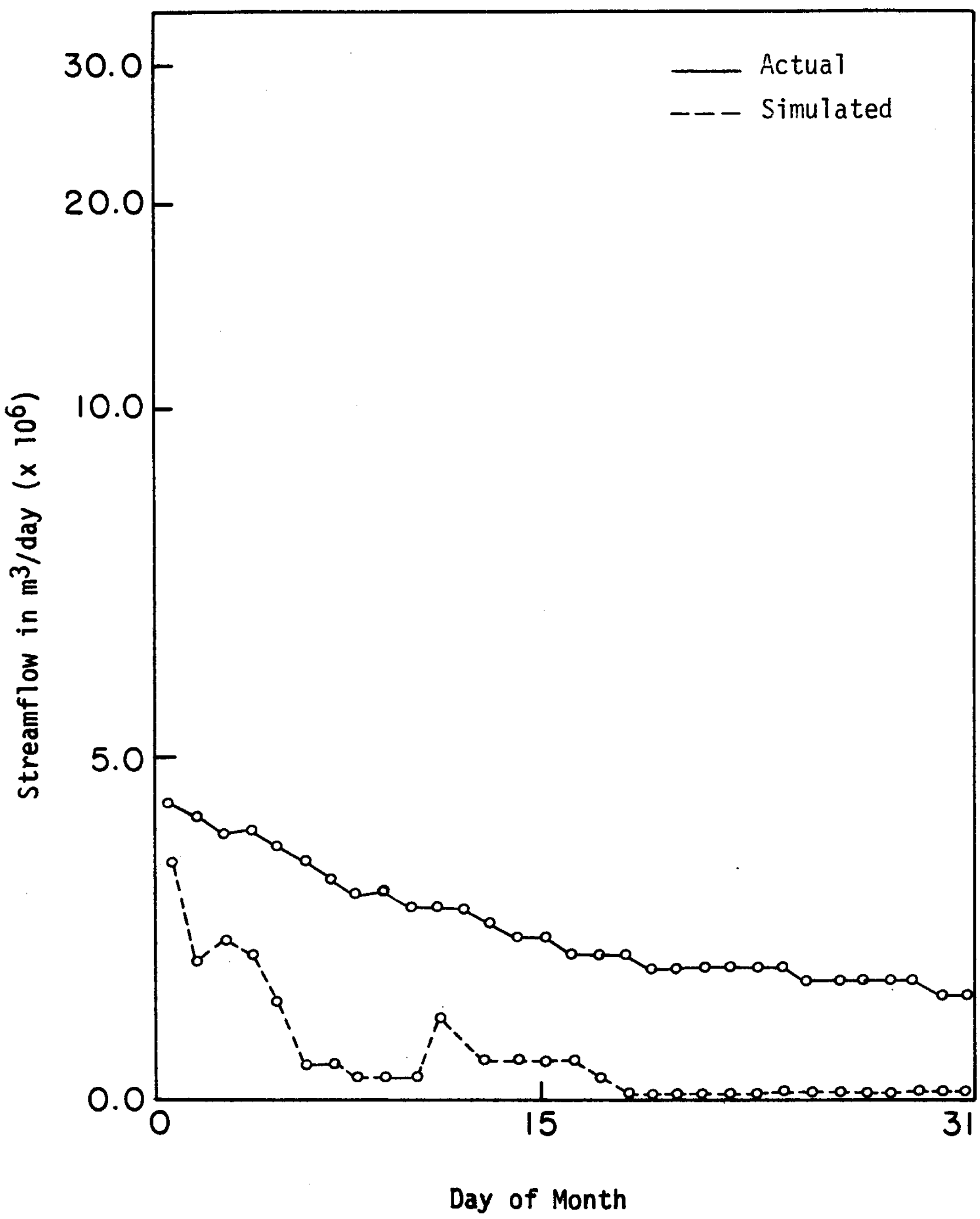

Figure 6b. Observed and Simulated Flows for the Toutle River Using Original CLS Model, July 1969

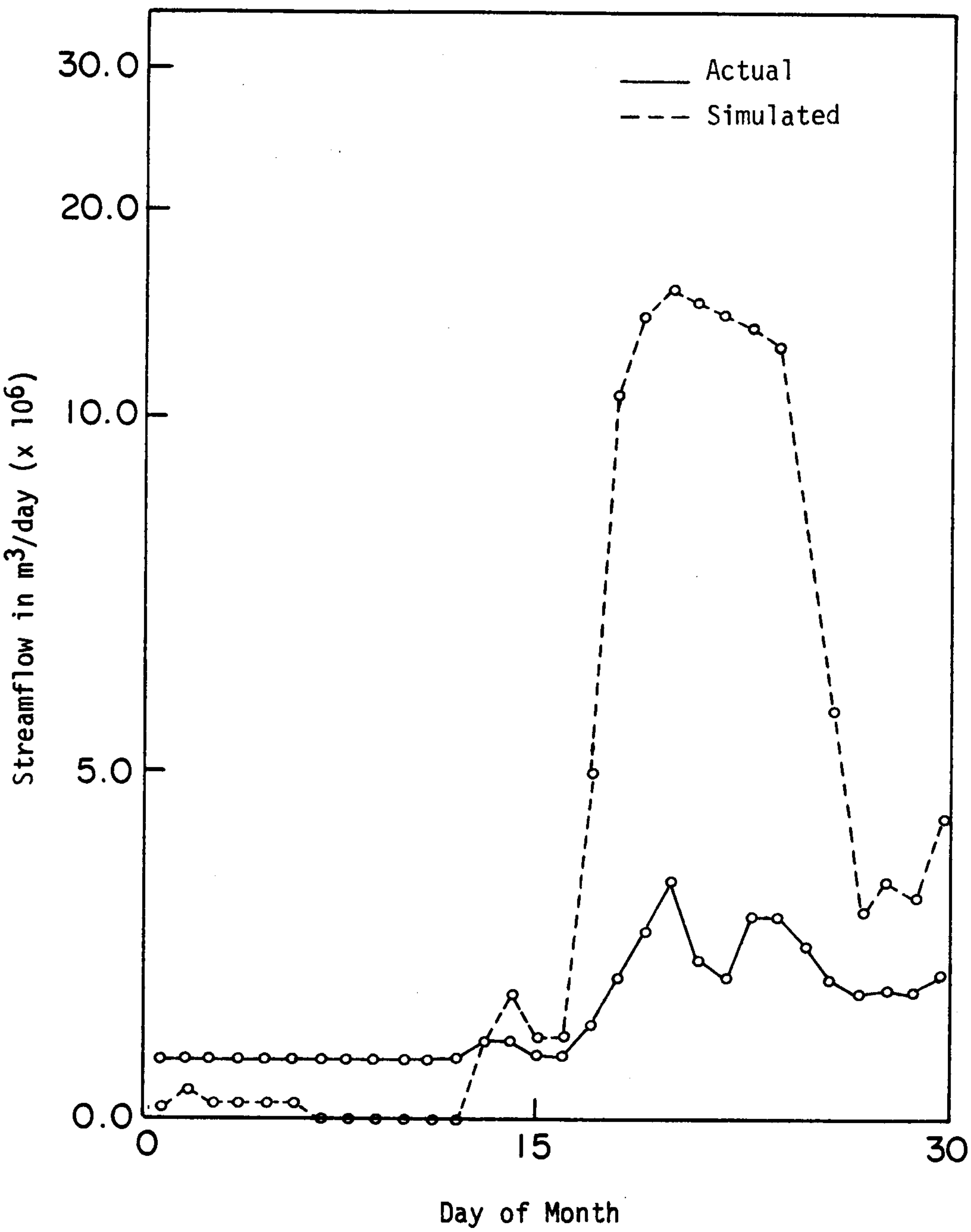

Figure 6c. Observed and Simulated Flows for the Toutle River Using Original CLS Model, September 1969

it is necessary to introduce parameters that relate to soil moisture conditions. Introduction of such parameters also modifies the absolute black-box character of the runoff model and where desirable, these parameters will allow the introduction of subjective judgement of the model builders. This flexibility is potentially important for water resource management problems.

In an attempt to incorporate an approximate but realistic accounting for the fraction of total precipitation lost in interception, depression, and infiltration, a model was constructed to preprocess the inputs and estimate the effective precipitation which would then be used as input to the CLS model. The results of this preprocessing model were encouraging; some of the most severe problems with the original CLS model were significantly reduced. Further investigation of results obtained using the modified CLS model in verification, as well as calibration mode confirmed the improvements in performance. Use of the preprocessor on the raw data incorporates the nonlinear and time variant behavior of the system. Additional refinements including time variability of some of the parameters should also be easy to accommodate.

Model Development

The original CLS model solves the discrete time-linear system in N inputs:

$$\underline{q} = \underline{Hu} + \underline{E} = \sum_{i=1}^{N} \underline{H}_i \underline{u}_i + \underline{E}$$

where u is a matrix of Nk impulse responses with k the length of each individual impulse response; q is an m-dimensional vector of discrete outputs for the time interval t, H is a partitioned matrix of discrete time inputs, and E is an error vector of dimension m.

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The CLS model minimizes the following functional:

$$J(\underline{E}'\underline{E}) = 1/2\underline{u}'\underline{H}'\underline{Hu} - \underline{u}'\underline{H}'\underline{q}$$

subject to the following optional choice of constraints:

1) No constraints (unconstrained ordinary least-squares).
2) $\underline{u} \geq 0$ implies that the impulse responses are non-negative.
3) $\underline{u} \geq 0$ and $\underline{Gu} = 1$ implies that the impulse responses are non-negative and imposes a water balance condition, for appropriate values of the vector $\underline{G}$.

In this formation, N is the number of input vectors, $\underline{q}$ is the outflow vector, $\underline{E}$ is a random error which takes into account modeling and data errors, and $\underline{u}_i$ is the ith impulse response. The input matrix $\underline{H}$ is composed of the input vectors $\underline{P}_i$, defined as:

$$\underline{P}_i = \begin{bmatrix} P_{i1} \\ P_{i2} \\ \cdot \\ \cdot \\ \cdot \\ P_{im} \end{bmatrix}$$

For a detailed explanation of the notation, the reader may refer to Martelli et al., 1977.

The effort reported in this paper is primarily concerned with the modification of the input vectors $\underline{P}_i$, from which the input matrix $\underline{H}$ is constructed. This was necessitated by the less that satisfactory simulated runoff volumes generated by CLS for the Toutle River simulations shown in Figures 6a through 6c.

The premise of the model development work was that the linear form of the CLS model could be made to form satisfactorily if effective precipitation were appropriately defined. Therefore, the preprocessing of the inputs amounts to computation of effective precipitation based on approximate storage conditions of the catchment. The preprocessing procedure consists of separately computing the contribution of total precipitation to depression storage, interception storage, and infiltration. The contribution to infiltration is computed based on the existing soil conditions. The assumptions made are empirical and simplified, compared to physics-based models. However, any resulting errors are compensated to some extent by the calibration process of the CLS model, which is based exclusively on the statistical relationship between effective precipitation and runoff.

The precipitation preprocessor assumes that the observed runoff results from precipitation that has passed through one of three different storage elements, or the impervious area as shown schematically in Figure 7. The overland flow caused by direct precipitation on impervious area, together with the overflow from the storage elements, is the total effective precipitation, which generates observed runoff when transformed by the impulse response function.

The contribution of total precipitation to infiltration is computed as a function of the contents of infiltration storage. The fraction of total precipitation actually entering the ground as infiltration is assumed to decay exponentially as this storage volume increases.

The most important component of the model is the computation of the amount of total precipitation that infiltrates. This computation is based on the accumulated soil moisture storage; therefore the fraction of precipitation that infiltrates is time-variant.

The following notations are used in the model:

k = non-negative recession constant

α = the fraction of gross precipitation appearing as direct runoff

C_1 = infiltration capacity when the existing infiltration storage is empty

C_2 = infiltration capacity when the existing infiltration storage is full

S_t = infiltration storage at the end of time period t

CAP = maximum possible infiltration storage

P_t^e = effective precipitation during time period t

D_t = contribution to depression storage during the time period t

IC_t = contribution to interception storage during the time period t

P_t^g = gross precipitation during time period t

I_t = infiltration during time period t

V_d = depression storage capacity

V_i = interception storage capacity

S_t^d = depression storage at the end of the period t

The fraction of gross precipitation appearing as direct runoff is defined as a function of the two limiting values C_1 and C_2. The infiltration capacity is assumed to decrease exponentially with increasing water content in the infiltration storage.

$$\alpha = C_2 + (C_1 - C_2)\, e^{-kS_{t-1}/CAP} \qquad (1)$$

The pattern of variation of α with S_t is shown in Figure 8.

The effective precipitation is defined as:

$$P_t^e = (1 - \alpha)\, P_t^g \qquad (2)$$

The portion of total precipitation infiltrating into ground storage is defined

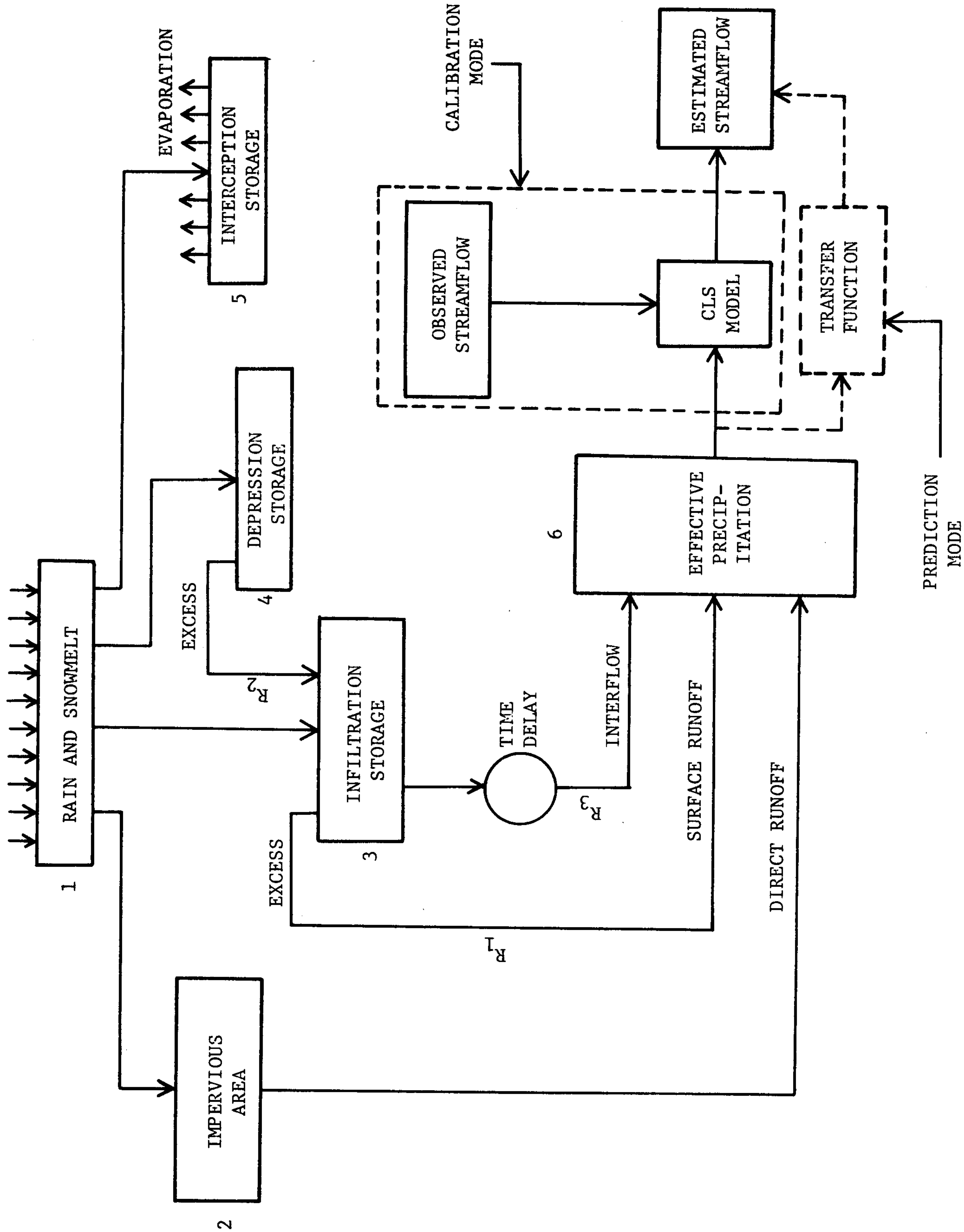

Figure 7. Schematic Diagram of Precipitation Preprocessor

as:

$$I_t = \alpha P_t^g \tag{3}$$

Infiltration storage at the end of time period t is defined as:

$$S_t = S_{t-1} + I_t - R_3 S_{t-1} \quad \text{for } S_t \leq CAP \tag{4a}$$

$$S_t = S_{t-1} + I_t - R_3 S_{t-1} - R_1(S_t - CAP) \quad \text{for } S_t > CAP \tag{4b}$$

Contribution of the precipitation to depression storage is defined as:

$$D_t = V_d(1-e^{-(1/V_d)P_t^e}) \tag{5}$$

The mass balance equation for the depression storage is given by:

$$S_t^d = S_{t-1}^d + D_t \quad \text{for } S_{t-1}^d \leq V_d \tag{6a}$$

$$S_t^d = S_{t-1}^d + D_t - R_2(S_{t-1}^d - V_d) \quad \text{for } S_{t-1}^d > V_d \tag{6b}$$

Contribution of precipitation to interception storage is defined as:

$$IC_t = V_i \ (1-e^{-(1/V_i)P_t^e}) \tag{7}$$

No mass balance is accounted for in the interception storage computation; however, this is negligible compared to other storage elements of the catchment. Alternately, this implies that the contribution of precipitation to interception storage is lost through evaporation.

The total contribution to streamflow is computed as a function of the effective precipitation and is assumed to consist of interflow, surface runoff and direct runoff. These components are described in Figure 7. The amount of precipitation contributing to direct runoff is a function of the infiltration storage condition. Therefore, the percentage of the catchment area behaving as impervious and thus contributing to direct runoff may be assumed to be a variable dependent on the water content in the infiltration storage. Surface runoff is assumed to occur as overflow from infiltration storage. If an overflow occurs from the depression storage element of the model, Equations 4a or 4b must be suitably modified to accommodate this additional inflow into the

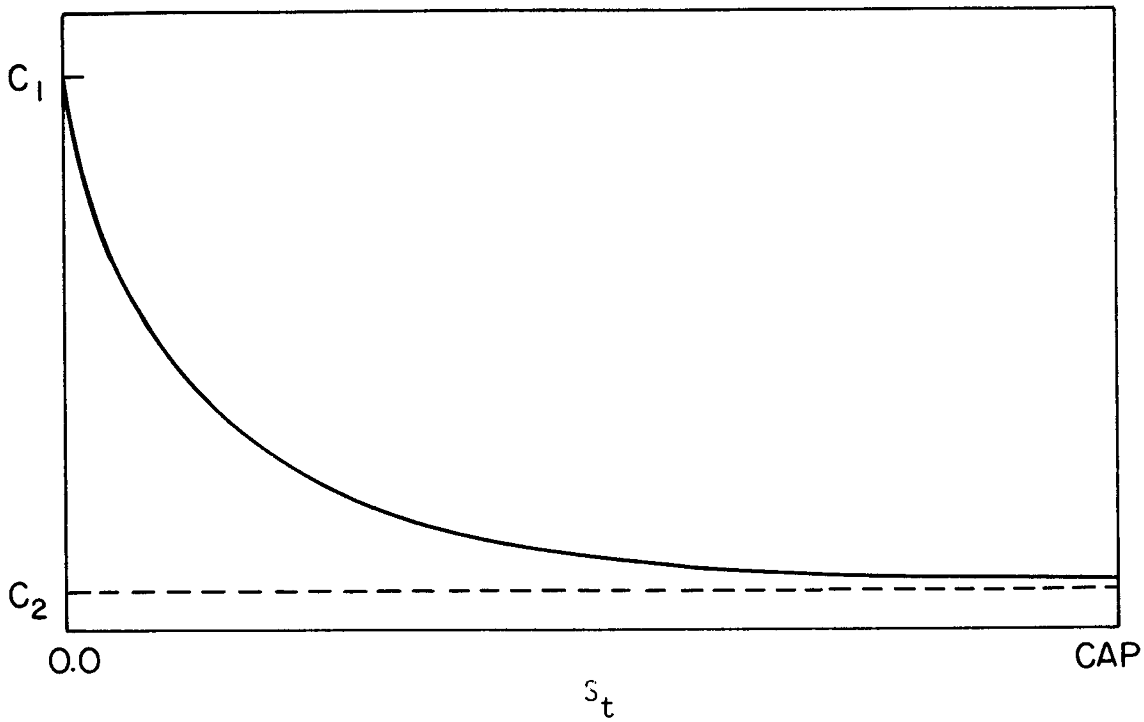

Figure 8. Pattern of Variation of α with Infiltration Storage S_t

storage. Interflow occurs from the bottom of the infiltration storage as a rate multiplied by the volume of storage in the previous time interval, with a time delay. These amounts may be expressed as:

1) Contribution from depression storage to infiltration storage = excess in depression storage * R_2
2) Surface runoff = excess in infiltration storage * R_1
3) Interflow = storage in infiltration storage * R_3

where R_1, R_2, and R_3 are calibration parameters.

The contribution of total pseudo precipitation (rainfall plus snowmelt) to streamflow is given by Element 6 in Figure 7 and is the input to the CLS model. The outflow from each contributing area of the basin is then computed using a single impulse response, which is assumed linear and time invariant. The catchment effects, which are in practice nonlinear and time variant, are accomodated entirely in the preprocessing model. The effects of using this preprocessing model together with the CLS model to simulate or predict streamflow were tested extensively and compared to those of using the CLS model alone with more than one response function per zone. The results will be discussed in Chapter IV.

Application of the modified model for simulating the Toutle River runoff is discussed in detail in the next chapter. The advantages of this model over the NWS River Forecast System Model (the runoff prediction part) and the original CLS model are also demonstrated. Use of the modified CLS model requires some experience with the catchment being modeled, as well as some intuitive judgment by the modelers, as is the case for all conceptual models. It is possible that the apparent performance of the model can be improved, in some cases, by specifying parameters which are not physically reasonable. Generally, such apparent improvements are slight, and can be guarded against by constraining the range of admissable parameters. A future improvement to the model might be implementation of an automated parameter estimation procedure. However, the method of trial and error fitting used here has the advantage of allowing incorporation of the users' subjective judgment and experience in the calibration process, and for this reason may be preferable.

CHAPTER III

MODELING OF THE PRECIPITATION-RUNOFF PROCESS

The critical aspect of simulating rainfall/snowmelt/runoff dynamics in mountainous regions is proper establishment of the precipitation-elevation relationship. Orographic effects predominate throughout most of the year in the mountainous regions of the Northwest. Therefore, precipitation generally increases with elevation; however, estimation of the rate of increase is difficult especially when many of the stations lie at low elevation. Precipitation estimation is further complicated by the susceptibility of high elevation stations to catch deficiency. As an example of the complexity of the precipitation-elevation relationship, Figure 9 shows the mean annual precipitation for seven stations in the vicinity of the Toutle River basin. With the exception of Cougar, the relationship is 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. It was found that particularly in the case of the Toutle catchment, this relationship is nonlinear. For these reasons, an adaptive approach to defining precipitation-elevation relationships was adopted.

Input Data Processing

The initial step in the implementation of the model consisted of manipulation of input data into a suitable form to drive the models. For the snowmelt/rainfall/runoff models used, input data are six-hourly precipitation and temperature. Daily runoff data were used to calibrate the models.

Handling of the runoff data was straightforward, as these are retrievable from the USGS WATSTORE automated data handling system in standard, 80 column card image format. No modifications were necessary for the University of Washington version of the original or modified CLS models. However, minor modifications were necessary for the NWS runoff model to allow files structured in the USGS format to be read directly. No missing data were encountered for the streamflow records used. Water years 1972 to 1982 were available through continuous updating of the available data, as the project progressed.

Precipitation and temperature data involve more cumbersome logistical exercises. Some of these data files were already set up for a similar study on the Toutle River. Details of the process are given in Lettenmaier and Burges (1981; Chapter III).

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. Because none of the stations used had records at less than a 24-hour increment, a process of disaggregation was necessary. The only station at which good quality (minimal missing data) records exist in Southwest Washington is at Olympia, approximately 55 miles northwest of the Toutle basin centroid. Although this station is more remote from the basin than is preferable, most winter storms in the Toutle basin result from Pacific frontal activity of large areal extent, so for the storms with greatest intensity this method may be acceptable. It was also noted in some limited sensitivity analysis (Lettenmaier and Burges, 1981) 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 aggregate total of the six-hourly predictions. Therefore, the disaggregation method is irrelevant when no snow is present. When snow is present it matters only when the precipitation occurs partly as snow and partly as rain. Also, 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 Weather Service (Anderson, 1973):

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

where $\underline{T} = (T_n\ T_m\ T_a\ T_e)'$:
n = 0000 - 0600
m = 0600 - 1200
a = 1200 - 1800
e = 1800 - 2400

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

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

and the coefficient matrix is:

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

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

The temperature relationships are shown in Figures 10 and 11 (reproduced from Lettenmaier and Burges, 1981). 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 annual average of about 2.5° F/1,000 ft below Longmire (elevation 2,760 ft), and about 3.6° F/1,000 ft above Longmire. However, Figure 7 shows that the nonlinearity is highly seasonal; during the months with highest precipitation (December -

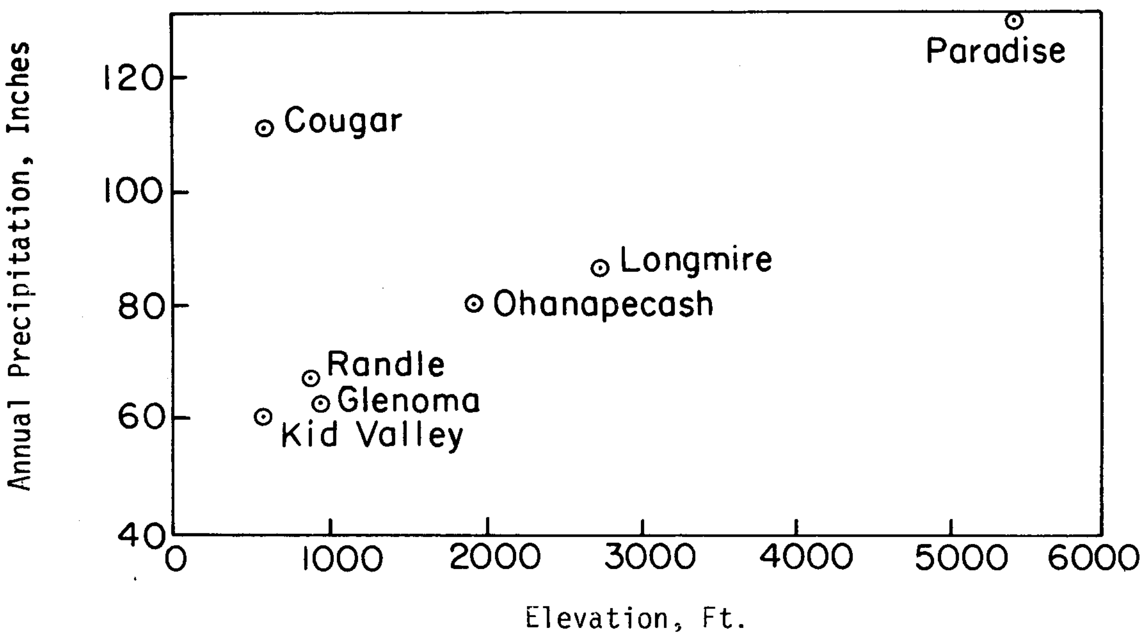

Figure 9. Mean Annual Precipitation vs. Elevation for Seven Stations in the Vicinity of the Toutle River Basin

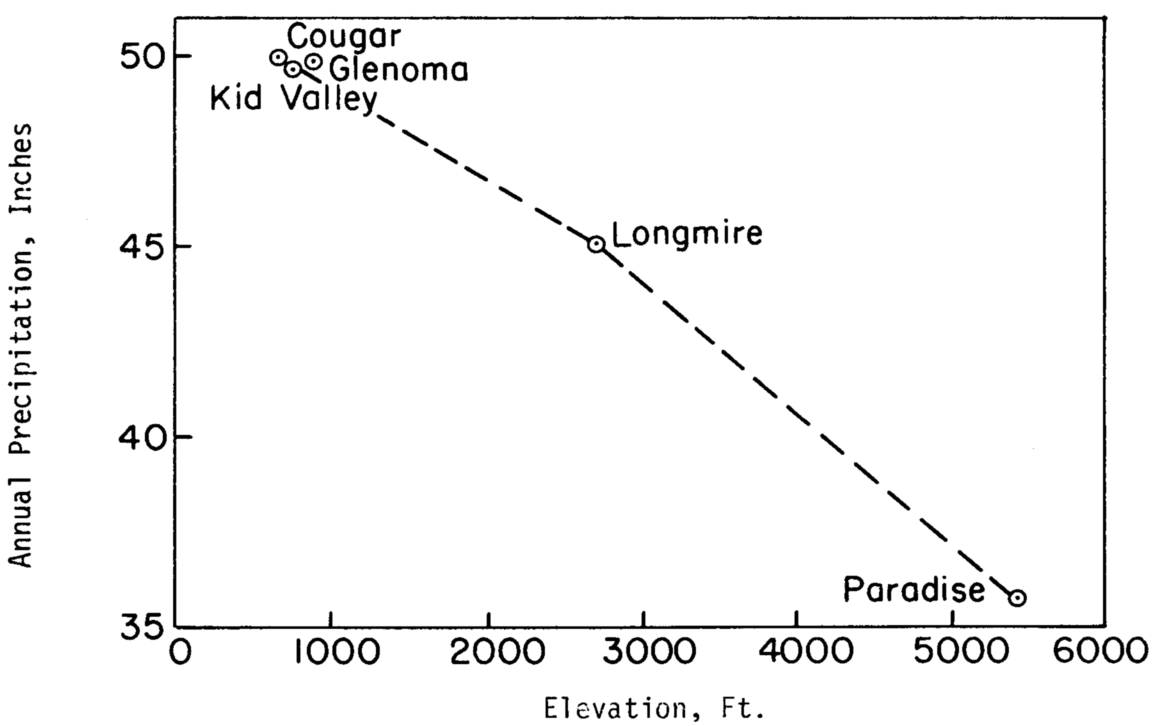

Figure 10. Mean Annual Temperature vs. Elevation for Five Stations in the Vicinity of the Toutle River Basin

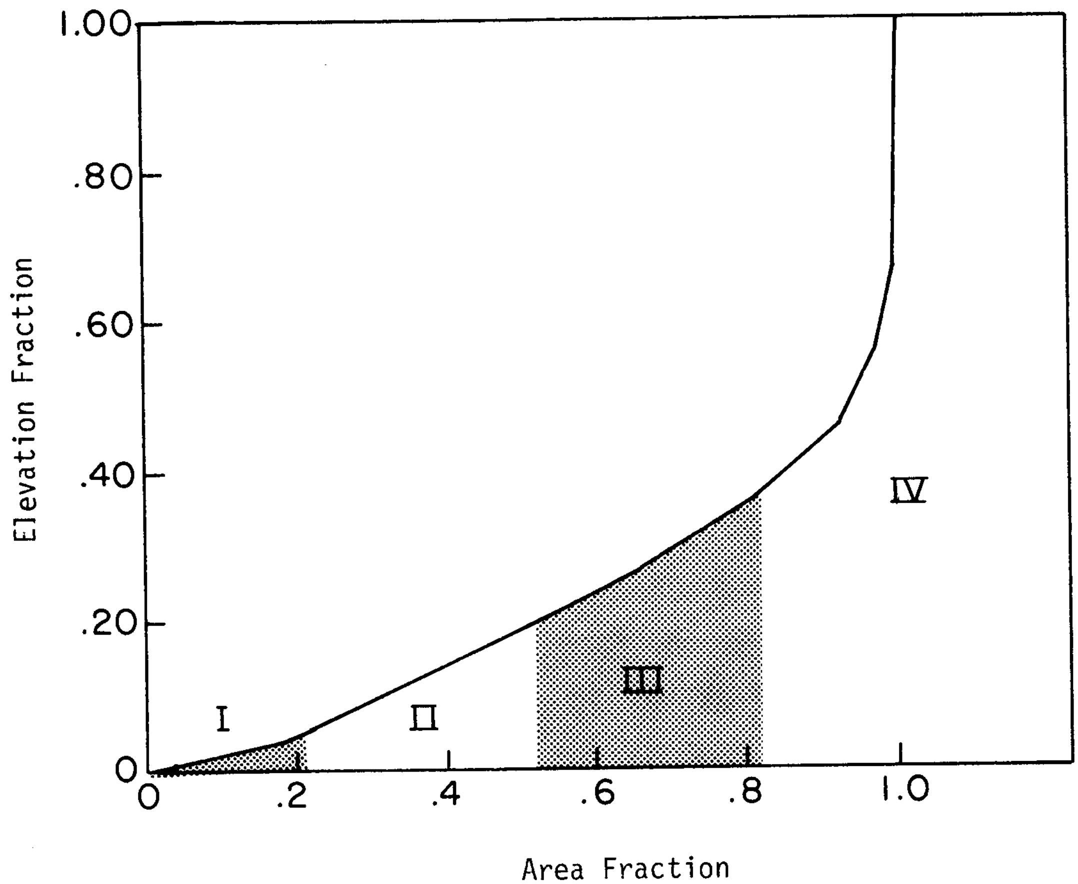

Figure 11. Normalized Hypsometric Curve for the Toutle River Basin with Elevation Zones

March) the lapse rate is nearly linear; which would be expected from meteorological considerations. For the purpose 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.

Partitioning of Elevation Zones

The rainfall-runoff models used, including the NWS runoff model, were structured to accept snowmelt and rainfall estimates from each of several elevation zones. In the case of the Toutle, four elevation zones were initially used. However, for the CLS and the modified CLS models these four elevation zones were aggregated to two elevation zones. As noted earlier, for Crab Creek only a single elevation zone was used.

The elevation ranges of the zones (Table 2) were selected through use of hypsometric curves, 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.

Table 2. Elevation Zones for the Toutle River Simulations

Zone	Elevation Range, ft	Median Elevation ft	Percent Basin Area
1	400-1000	700	22
2	1000-2000	1500	30
3	2000-3500	2700	30
4	3500-	4100	18

For each elevation zone, one precipitation gauge was assumed to characterize best the average precipitation in that zone. Table 3 shows the stations selected for each zone. The selection was based on physical proximity of the stations, as well as other considerations that 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 most representative of high elevation conditions). Finally, it should be noted that the raw station records were used (constant multipliers) to estimate areal precipitation appropriate to each elevation zone, as given in Table 4. For the CLS and the modified CLS models, the total pseudo precipitation records as obtained from the snowmelt model were combined for Zones 1 and 2 and also Zones 3 and 4. Sensitivity analysis confirmed that, unlike the NWS runoff model, aggregation of zones did not affect the accuracy of the CLS model.

Table 3. Precipitation and Temperature Gauge Representing Various Elevation Zones for the Toutle River Basin

Zone	Precipitation	Temperature
1	Kid Valley	Kid Valley
2	Glenoma	Longmire-Paradise (interpololation)
3	Cougar	Longmire + 0.5°C
4	Cougar	Paradise + 2.0°C

Table 4. Precipitation Station Multipliers, the 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)

Snow Course Selection

It was found that the observed snow water equivalents at the limited snow courses in the area did not characterize elevation zone mean conditions, hence the available records were of minimal use for calibration of the models. The data did, however, 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 Spokane Airport for Crab Creek.

Elevation Adjustment of Temperature and Precipitation

Following disaggregation of the raw meteorological data to a six-hour time base, adjustments were made to provide representative records for each elevation zone. Such adjustments were not necessary for Crab Creek, because only one elevation zone was considered.

The adjustments were achieved by selecting a station whose physical characteristics (elevation and geographic coordinates) were thought to be representative of the zone, as discussed before. Subsequently, temperature records were adjusted to 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 1 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 1. This linear precipitation-elevation relationship was used as an initial approximation. The relationship could also be changed by adjustment of the precipitation factor in the snowmelt model; however, this factor was initially set to 1.0 in the interest of minimizing the number of calibration parameters. Unfortunately, the precipitation and temperature recording station at Kid Valley was destroyed in the May 16, 1980 eruption and was not replaced. Therefore, the post-eruption records for this station were reconstructed by multiplying the records at Glenoma (due to its elevation compatibility to Kid Valley) by a factor equal to the ratio of the historical monthly means of the two stations. Once the initial models for processing of raw data were implemented, the normal calibration process, consisting of trial and error adjustment of model parameters and precipitation and temperature factors, was followed.

CHAPTER IV

IMPLEMENTATION OF THE NWS (RUNOFF) AND MODIFIED CLS MODELS FOR THE TOUTLE RIVER

The implementation and calibration of the NWS runoff model for the Toutle River was carried out as an initial approximation. However, as discussed in the previous chapter, the simulation results for the best possible calibration had some drawbacks. Specifically, for the month of September, when a series of high flows occurred following a long dry spell, the NWS model simulated hydrographs with peaks nearly 300 percent higher than the recorded flows. Success in simulating the recession flows was limited as well. Also, because a statistical approach to assessing the changes in response of the catchments was taken, use of a model based on a statistical process of calibration rather than the water balance method used by the NWS soil moisture accounting model was favored. The CLS model as described before, was adopted for this reason. However, the best possible calibration obtained for this model even with more than one impulse response function, was far less than satisfactory. Hence, some modifications were implemented to preprocess the gross precipitation used as input to this model. These modifications are described in Chapter II. The calibration of this modified model for the Toutle River for pre-eruption conditions is described in the following sections.

Calibration of the Modified Model

The values of the parameters specified after some trial and error methods of calibration (see Chapter II for description of parameters) were:

$R_1 = 0.90$

R_2 = 0.90

R_3 = 0.02

k = 0.90

V_d = 2.54 cm

CAP = 8.90 cm

V_i = 0.25 cm

C_1 = 0.70

C_2 = 0.10

Initially the preprocessing model and the CLS model were run for a calibration period from October 1972 to September 1976 for the Toutle River. A detailed description of this basin including the snowmelt model used to derive the pseudo-precipitation record was given in the previous chapter. The calibration involved the by eye estimation of the parameters given above and the estimation of the parameters of the impulse response function for the CLS model using the usual method. The performance of the model as evaluated by different statistical measures is summarized in Table 5. In prediction mode, the impulse response function parameters found in the calibration mode were used to predict the streamflow volumes, for a given pseudo-precipitation record.

Table 5. Summary of Results of Application of CLS with Precipitation Preprocessor to the Toutle River

Calibration Mode Water Years 1973-76 Description	Value	Prediction Mode Water Years 1977-80 Description	Value
Mean of residuals	-.0003	Mean of residuals	.0154
Standard deviation of residuals	.0583	Standard deviation of residuals	.0491
Determination coefficient	.9087	Determination coefficient	.8843
Percent error between peaks	-21.29	Percent error between peaks	-3.44
Maximum observed runoff	2.0478	Maximum observed runoff	2.3067

The percentage error betwen peaks, standard deviation of residuals, and the coefficient of determination as obtained from the original CLS model with two response functions for each subdrainage (threshold API value of 12.7 cm for M = 10 days) are given in Table 6 for water year 1969, which is somewhat typical of the relative performance of the models. Considerable improvement in prediction accuracy using the CLS model with the precipitation preprocessor was found for an independent verification period, as shown in Table 6. Figures 12a - 12c illustrate the performance of the modified model.

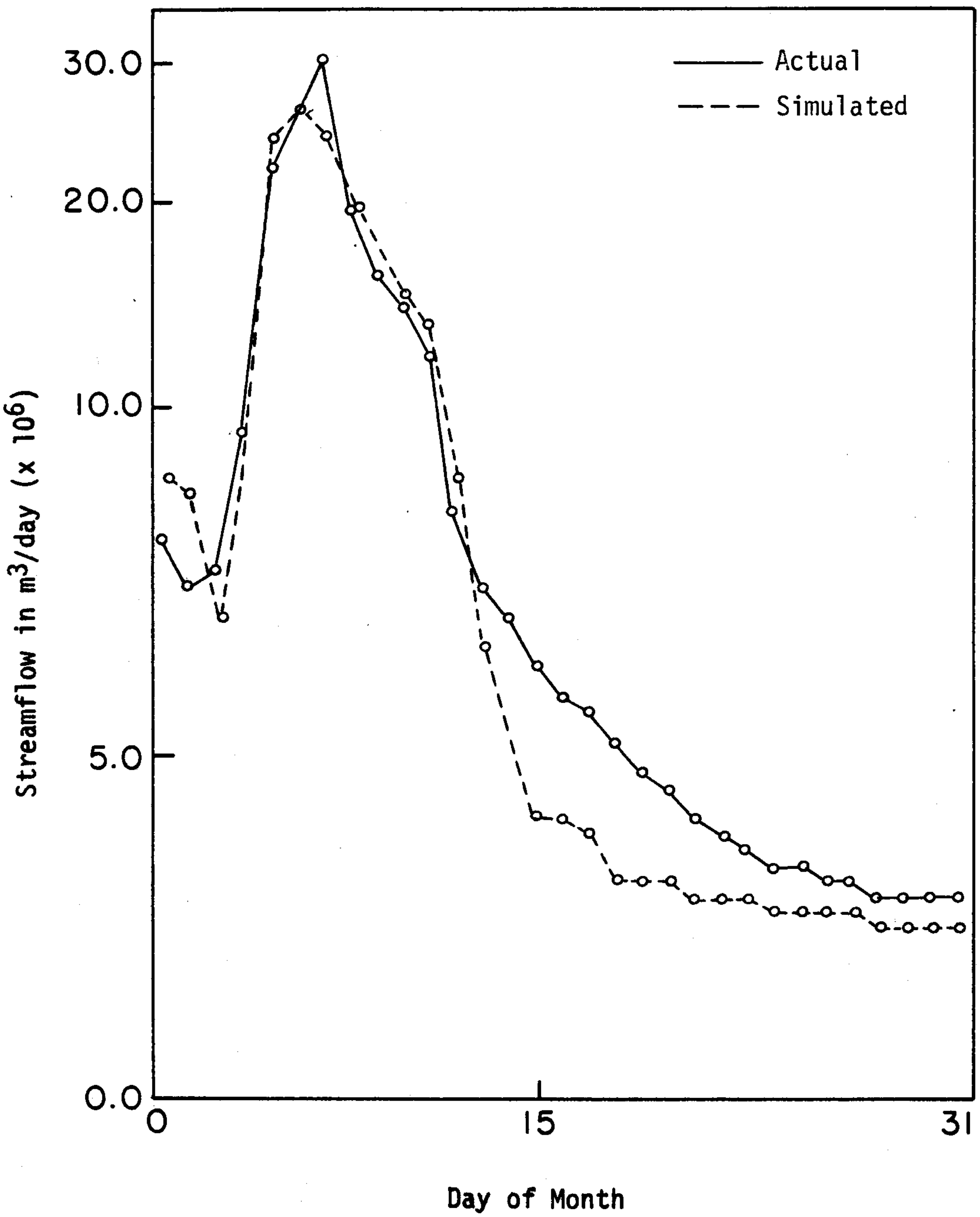

Figure 12a. Observed and Simulated Flows for the Toutle River Using the Modified CLS Model, January 1969.

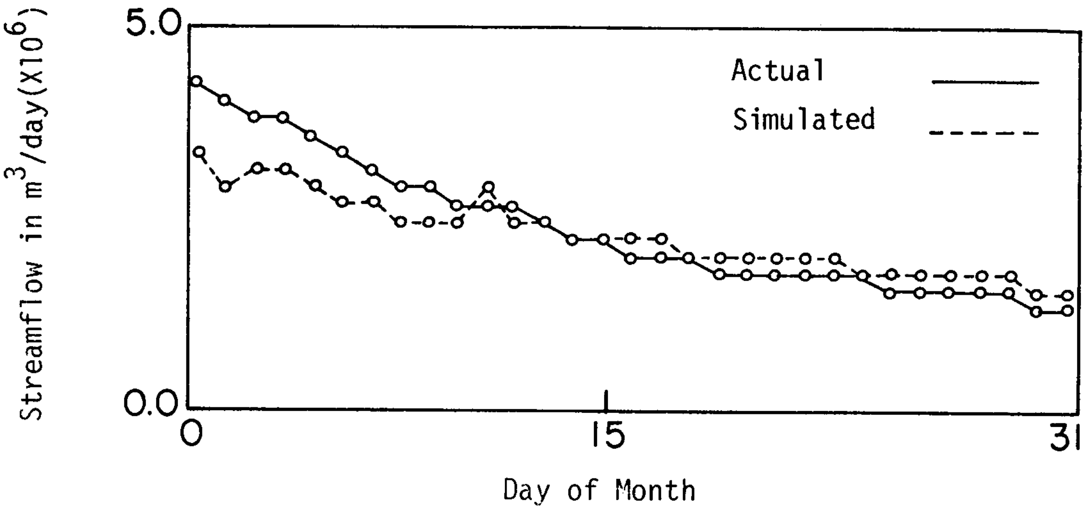

Figure 12b. Observed and Simulated FLows for the Toutle River Using the Modified CLS Model, July 1969

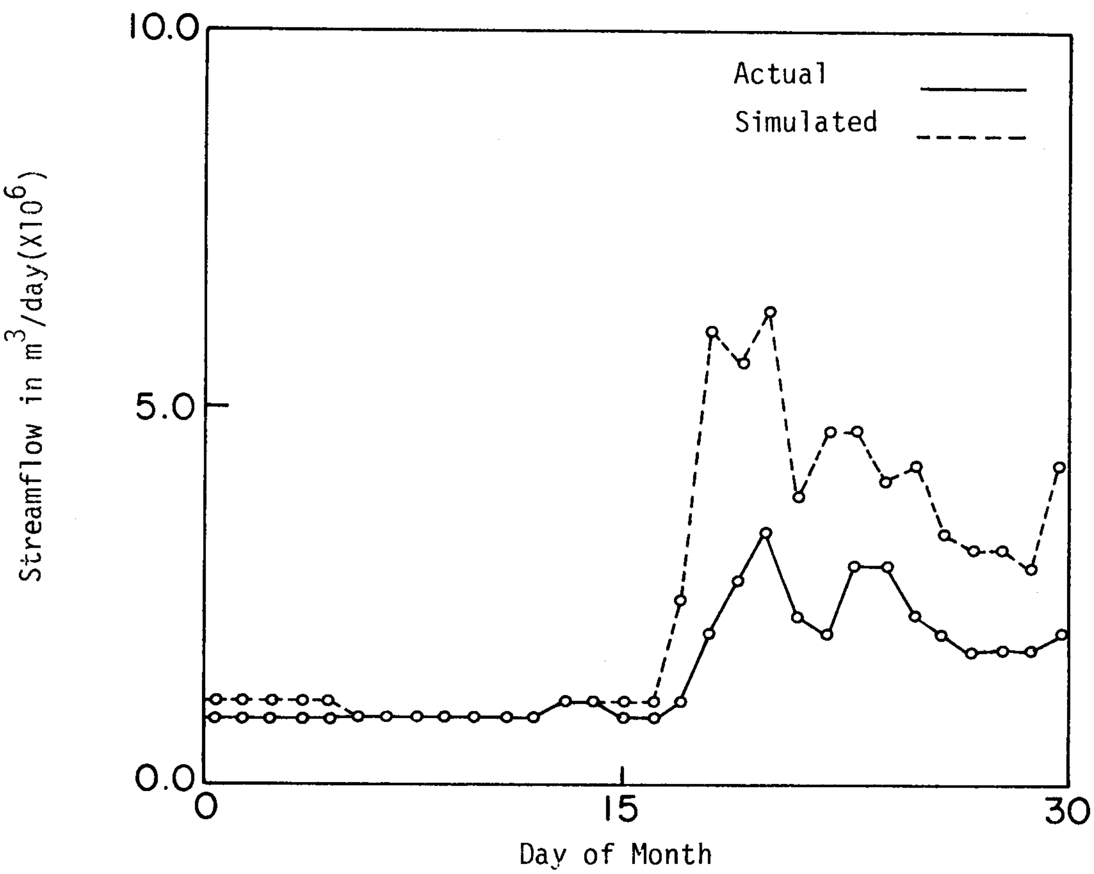

Figure 12c. Observed and Simulated Flows for the Toutle River Using the Modified CLS Model, September 1969

Table 6. Performance of Original CLS Model and the Modified Model with Single Impulse Response During Independent Verification

Original CLS Model Water Year 1969		Combined Model Water Year 1969	
Description	Value	Description	Value
Mean of residuals	-.0305	Mean of residuals	-.0265
Standard deviation of residuals	.0833	Standard deviation of residuals	.0476
Determination coefficient	.8607	Determination coefficient	.5741
Percent error between peaks	25.76	Percent error between peaks	-12.66
Maximum observed runoff	1.00	Maximum observed runoff	1.00

It was found from a visual investigation of the simulated and observed runoff plot for daily flows that the new model was able to simulate the recession parts of the hydrograph, a severe limitation in the original CLS model. However, for intermediate flow ranges the combined model still had some relatively large errors. To overcome this deficiency in the model, it was decided to transform the input and outputs to the CLS model, so that the tendency of the CLS model to overfit the high flows compared to the low flows (to achieve a lower variance of the residuals) could be reduced. An attempt to transform only the runoff data was rejected because of poor results and also because transformation of the runoff alone has the undesirable effect of making the convolution used in CLS nonlinear, with unknown properties.

Square root transformations were used subsequently on the effective precipitation and observed runoff simultaneously, and the impulse response functions for these transformed inputs and outputs were computed. The results were encouraging; the quality of fit obtained from the transformed inputs and outputs was found to be much improved, as shown by the statistical properties of the errors shown in Table 7. Figures 13a - 13c, when compared with Figures 5a - 5c establishes the suitability of this transformation in the modified model.

Table 7. Summary of Performance of the Modified Model with Square Root Transformation of Input and Output

Calibration Mode Water Years 1973-76		Prediction Mode Water Years 1977-80	
Description	Value	Description	Value
Mean of residuals	.0033	Mean of residuals	.0151
Standard deviation of residuals	.0647	Standard deviation of residuals	.0448
Determination Coefficient	.8641	Determination coefficient	.9052
Percent error between peaks	-34.66	Percent error between peaks	-21.13
Maximum observed runoff	2.0478	Maximum observed runoff	2.3067

To demonstrate the relative advantage of using the combined model with the square root transformation, a water year with a very low flow (1977) was chosen for comparison. Table 8 shows some of the results.

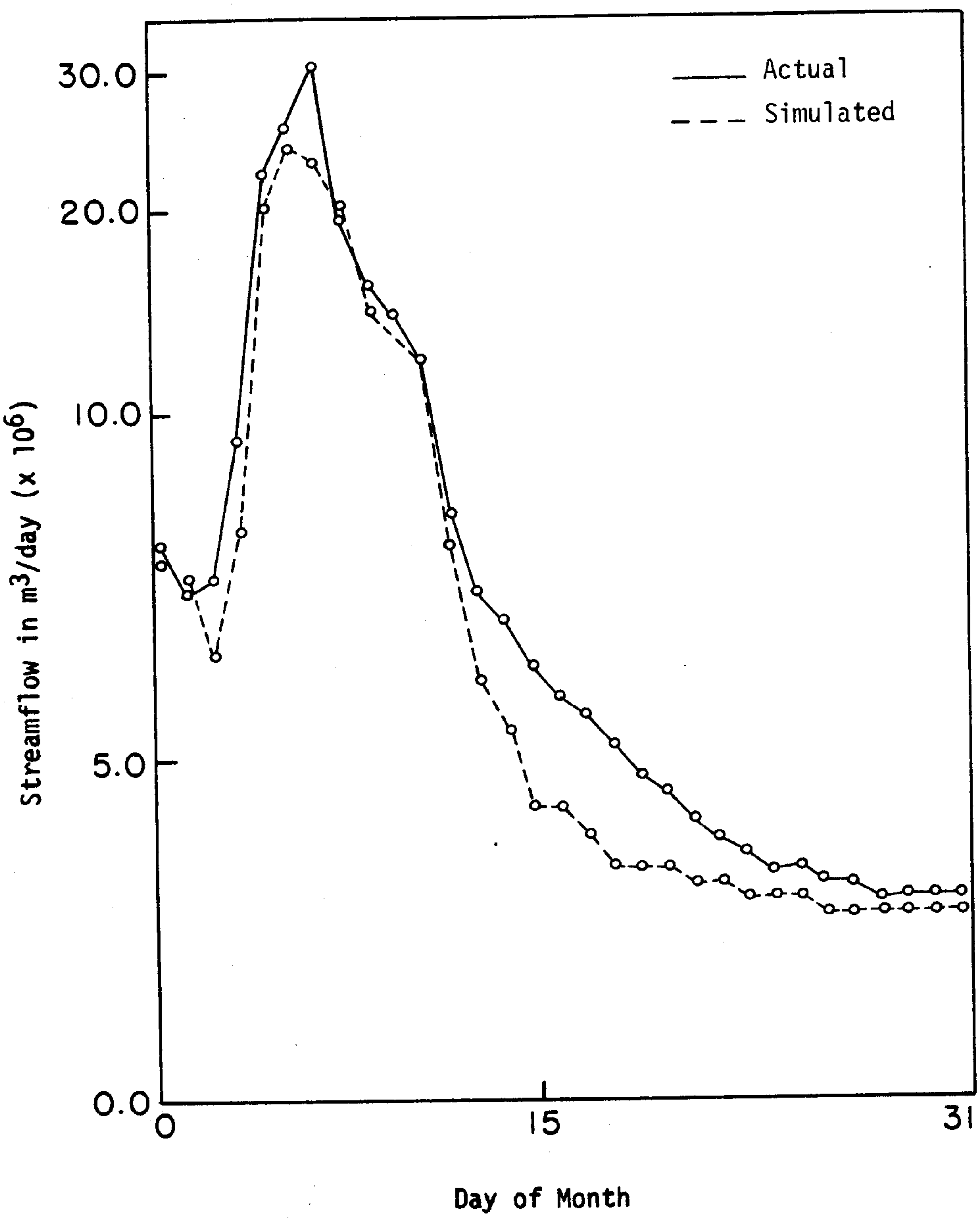

Figure 13a. Observed and Simulated Flows for the Toutle River Using the Modified CLS Model with Square Root Transformation, January 1969

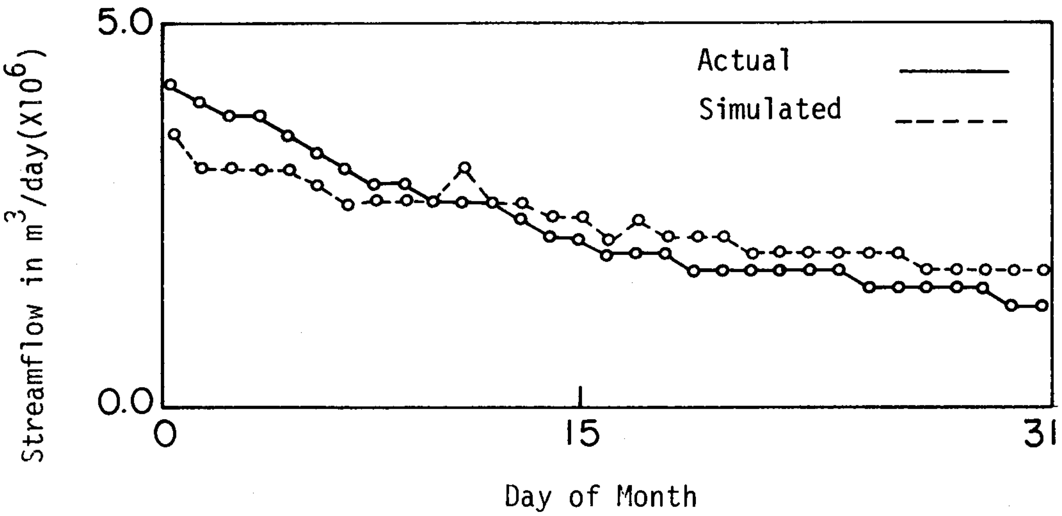

Figure 13b. Observed and Simulated Flows for the Toutle River Using the Modified CLS Model with Square - Root Transformation, July 1969

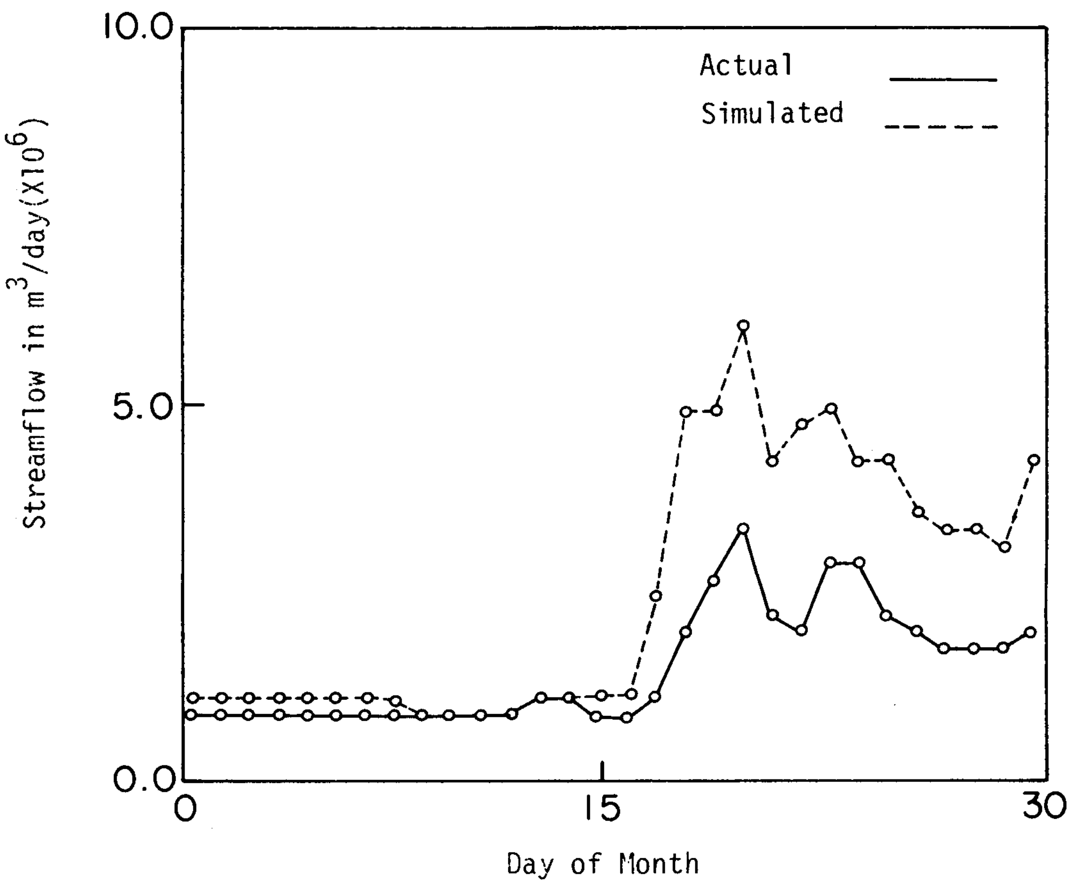

Figure 13c. Observed and Simulated Flows for the Toutle River Using the Modified CLS Model with Square Root Transformation, September 1969

Table 8. Summary of Performance of the Modified Model with and without Square Root Transformation for Water Year 1977

Prediction Mode With Square Root Transformation Water Year 1977		Prediction Mode Without Square Root Transformation Water Year 1977	
Description	Value	Description	Value
Mean of residual	.0198	Mean of residual	-.195
Standard deviation of residuals	.0374	Standard deviation of residuals	.0432
Determination Coefficient	.8607	Determination Coefficient	.5741
Percent error between peaks	.3527	Percent error between peaks	3.8175
Maximum observed runoff	.3743	Maximum observed runoff	.3743

It is evident from Tables 7 and 8 that for years of relatively low precipitation, use of the model without transformation in prediction mode may result in determination coefficients much lower than the determination coefficient obtained for an aggregate of a few years at a stretch. This is primarily due to the tendency of the CLS model to give higher weight to the higher flows in the fitting process. Better reproduction of low flows can be accomplished by transformations as described or by weighing the inputs and outputs relative to their magnitude. It is also evident from Table 9 that the square root transformed model gives more consistent determination coefficients for all the years taken separately in the prediction model than does the untransformed model. This result may be particularly useful in studying the change of responses of a catchment under external intervention. Figure 14a - 14e and Figures 15a - 15e give a comparative assessment of the performance of the modified model without and with transformation in prediction mode.

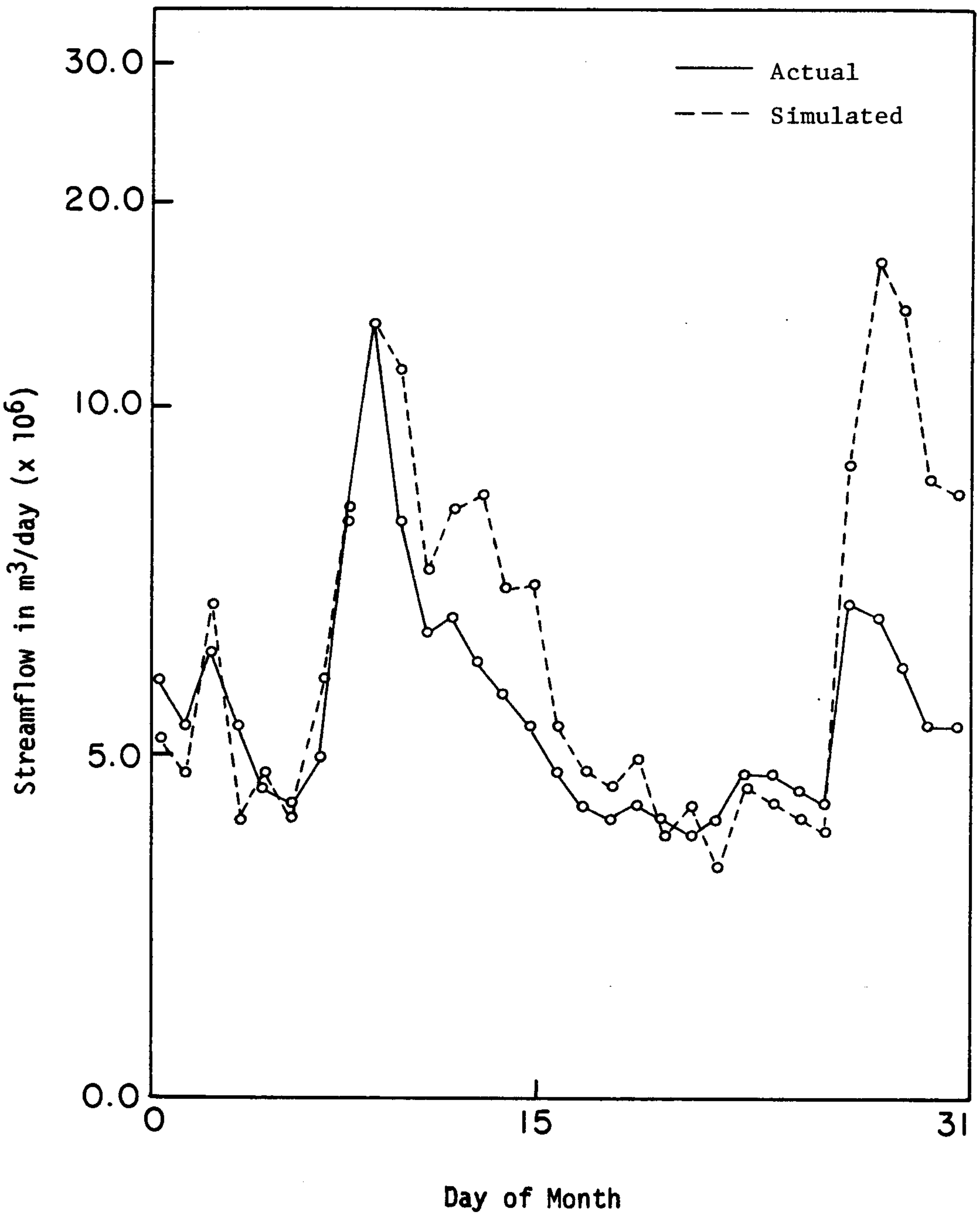

Figure 14a. Observed and Predicted Flows for the Toutle River Using the Modified CLS Model in Prediction Model, March 1977

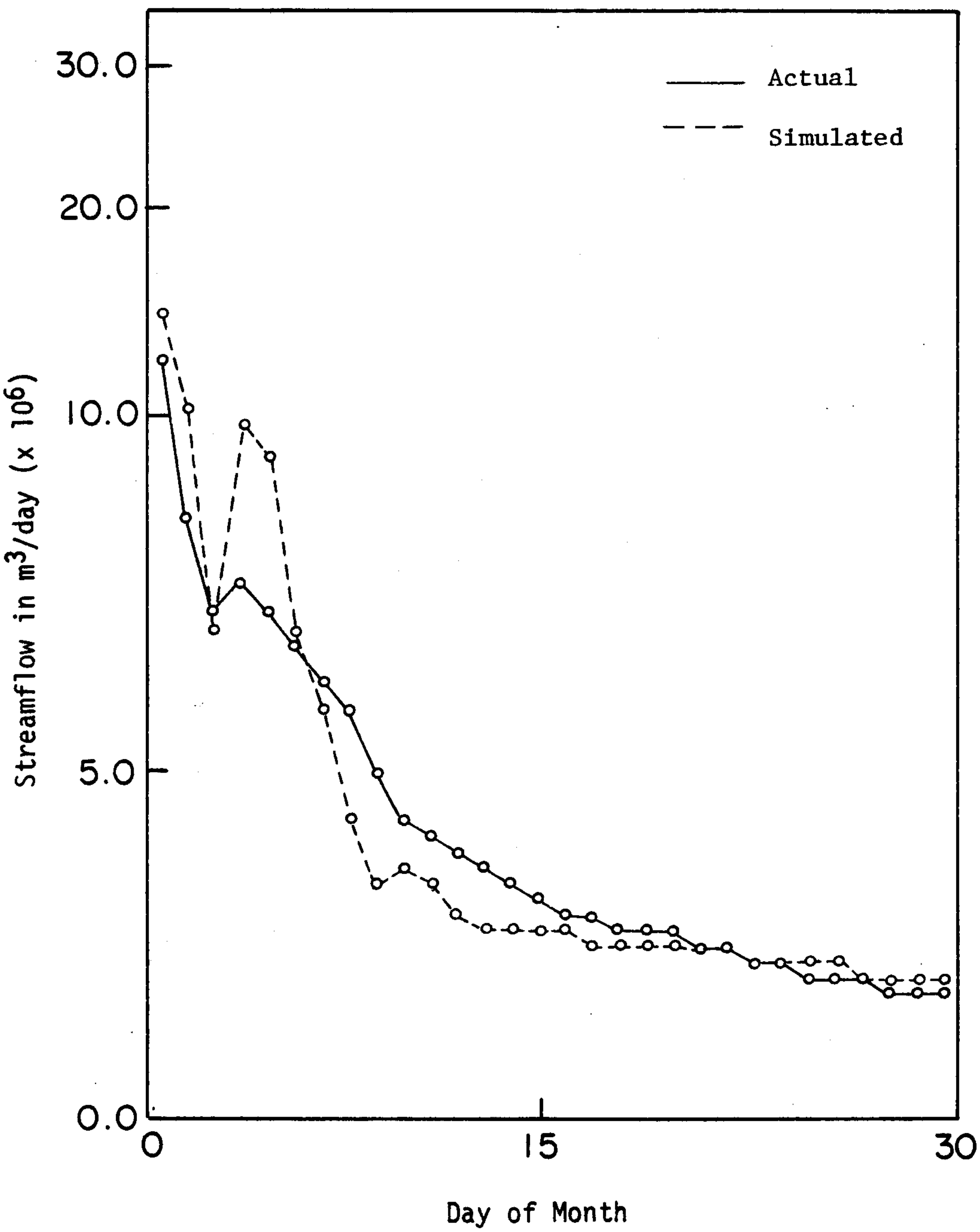

Figure 14b. Observed and Predicted Flows for the Toutle River Using the Modified CLS Model in Prediction Mode, June 1977

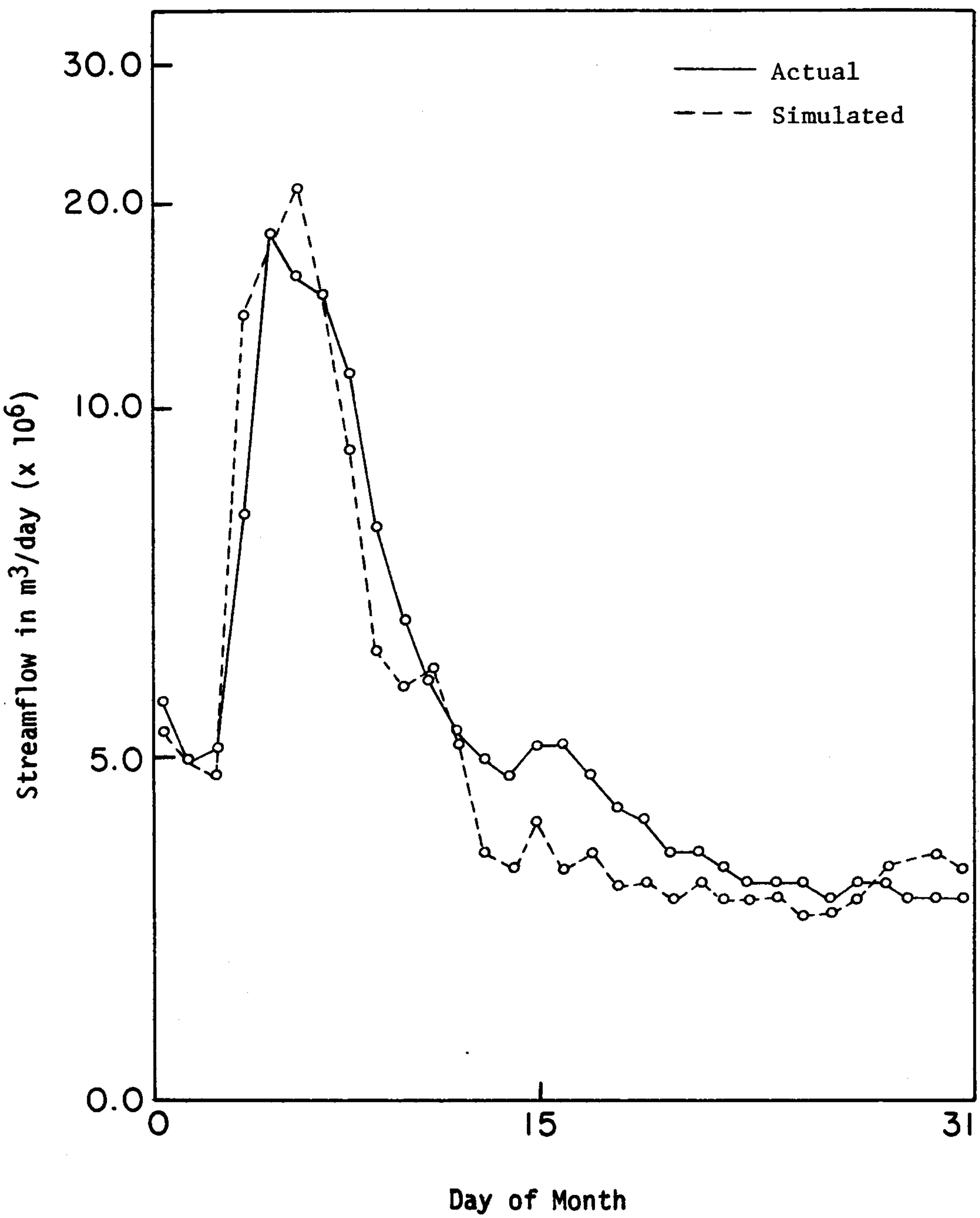

Figure 14c. Observed and Predicted Flows for the Toutle River Using the Modified CLS Model in Prediction Mode, March 1979

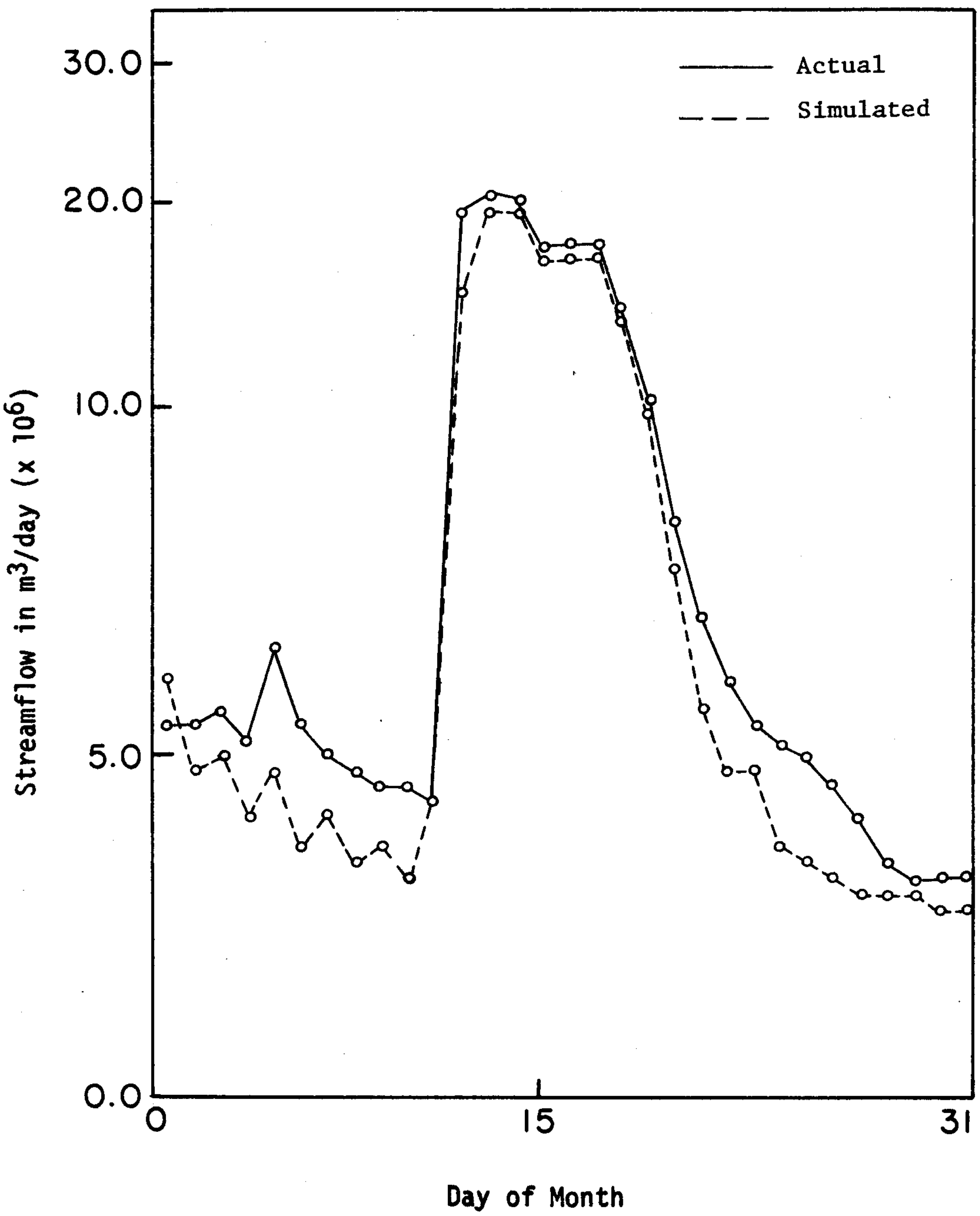

Figure 14d. Observed and Predicted Flows for the Toutle River Using the Modified CLS Model in Prediction Mode, January, 1980

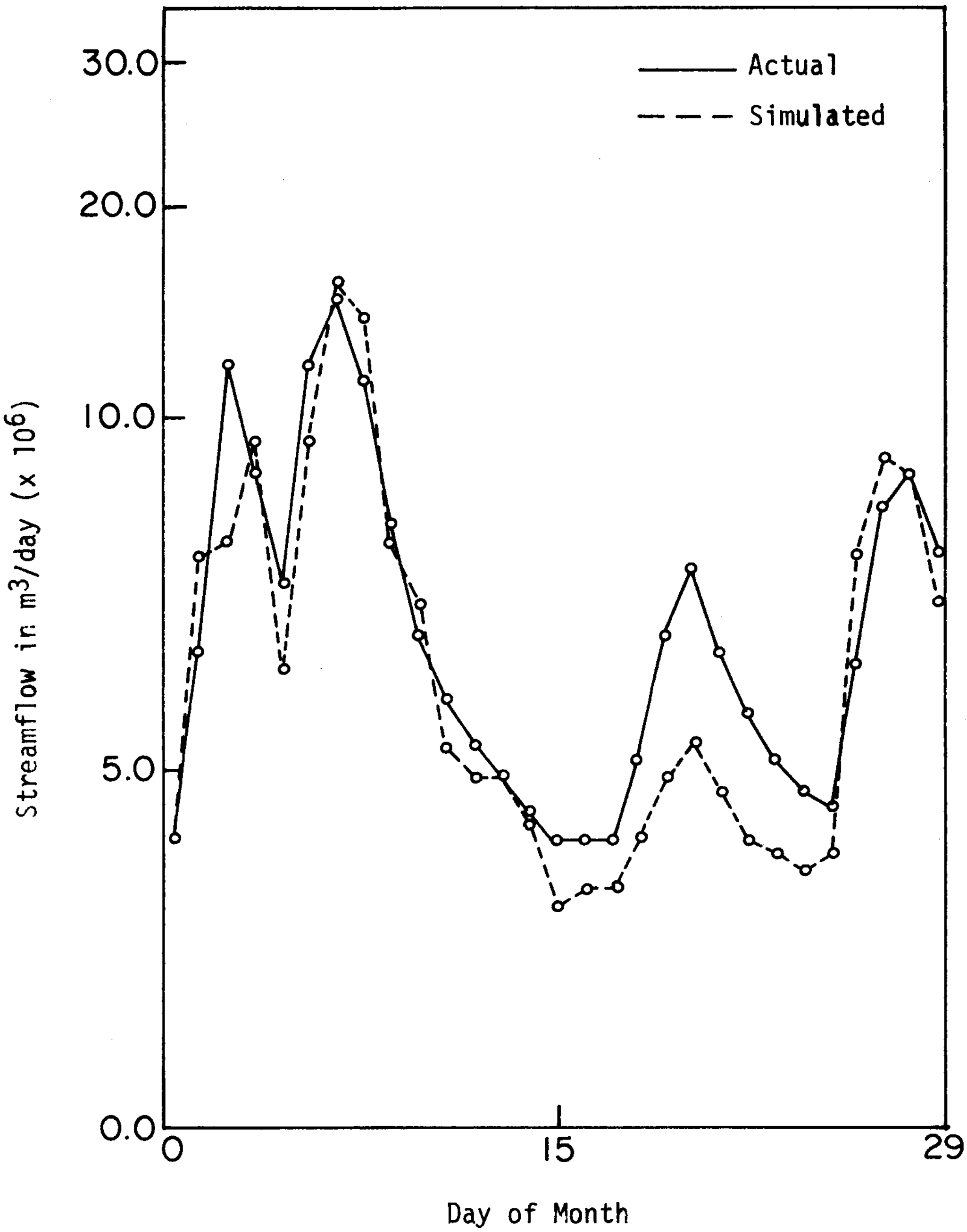

Figure 14e. Observed and Predicted Flows for the Toutle River Using the Modified CLS Model in Prediction Mode, February 1980

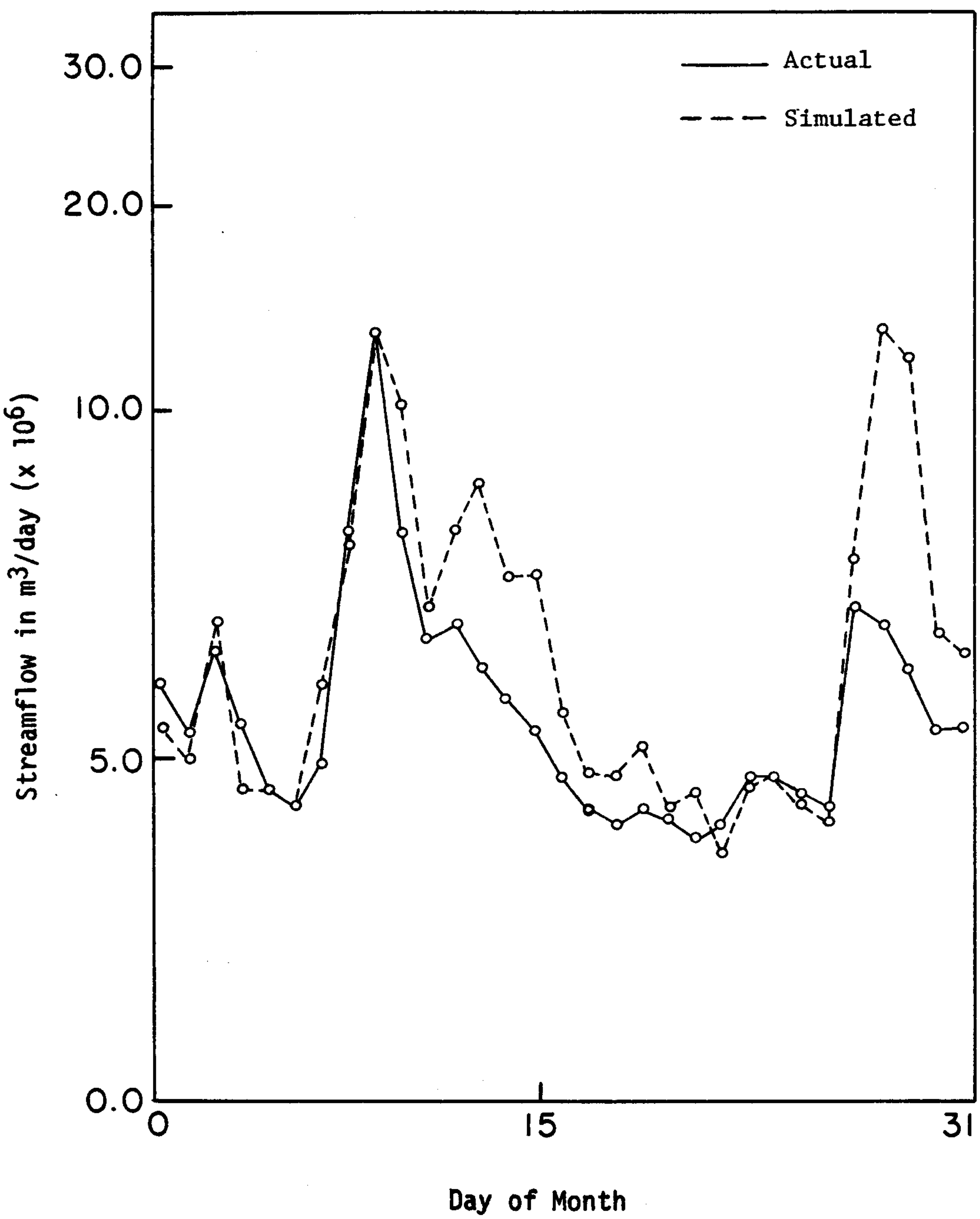

Figure 15a. Observed and Predicted Flows for the Toutle River Using the Modified CLS Model with Square Root Transformation in Prediction Mode, March 1977.

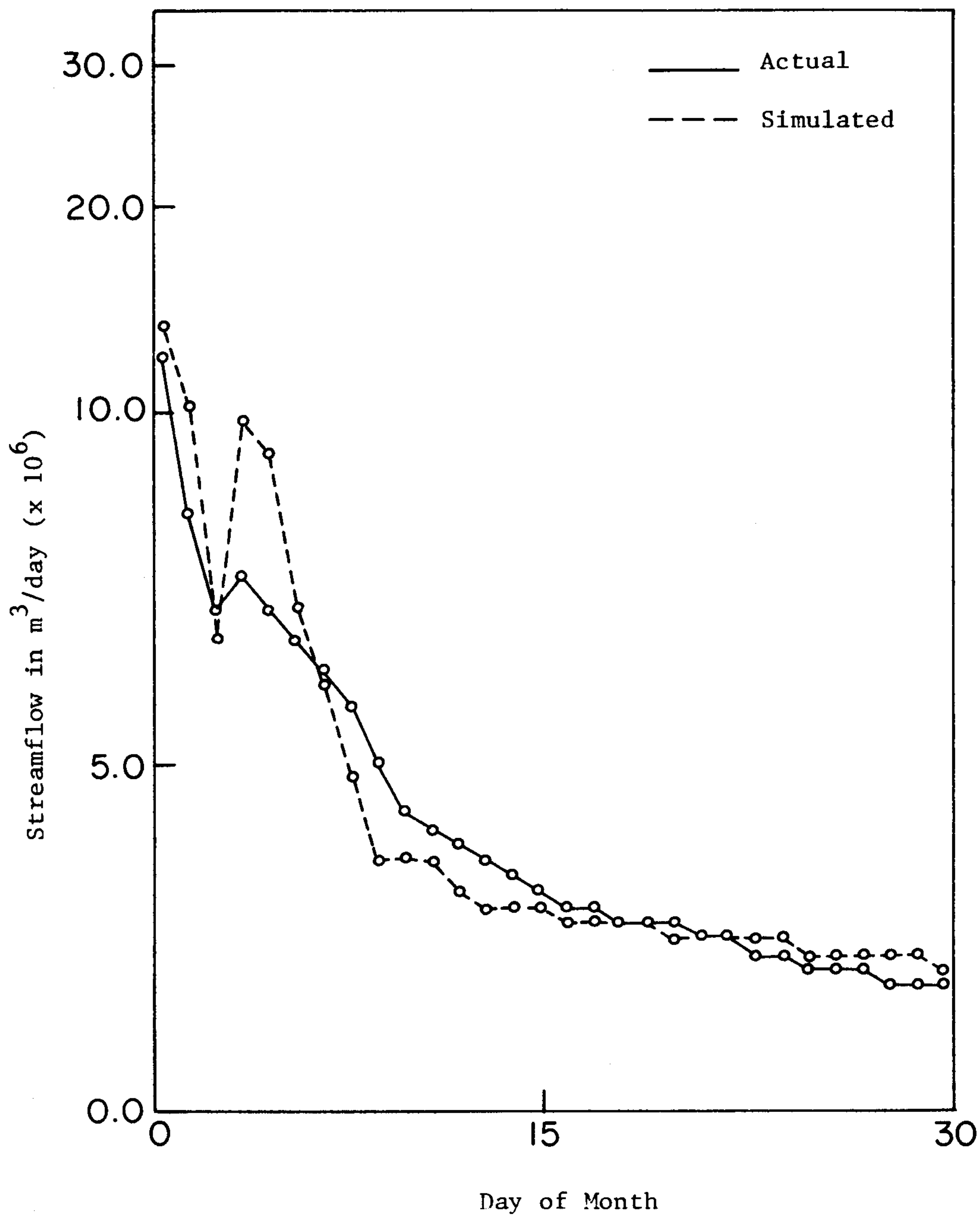

Figure 15b. Observed and Predicted Flows for the Toutle River Using the Modified CLS Model with Square Root Transformation in Precipitation Mode, June 1977

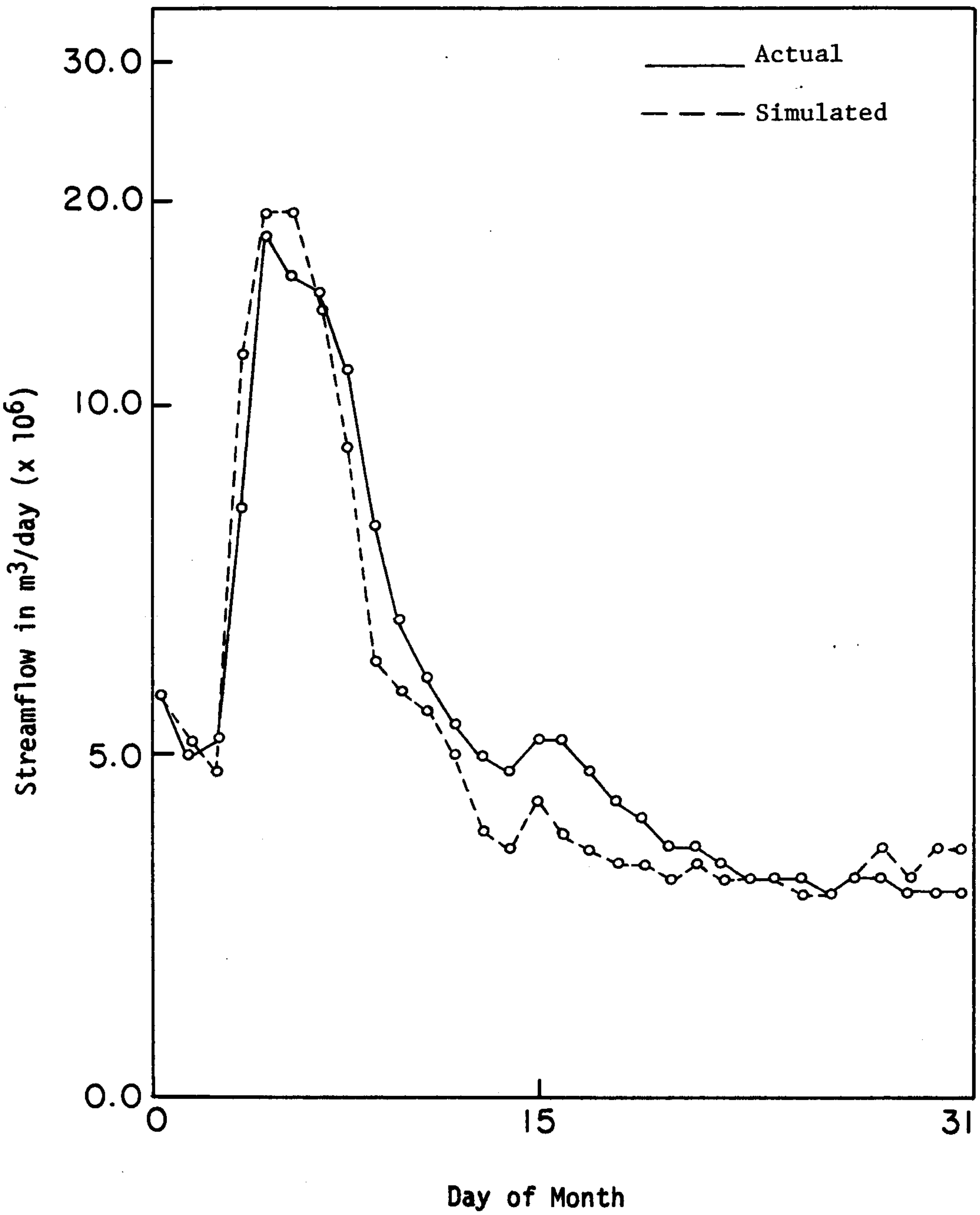

Figure 15c. Observed and Predicted Flows for the Toutle River Using the Modified CLS Model with Square Root Transformation in Prediction Mode, March 1979

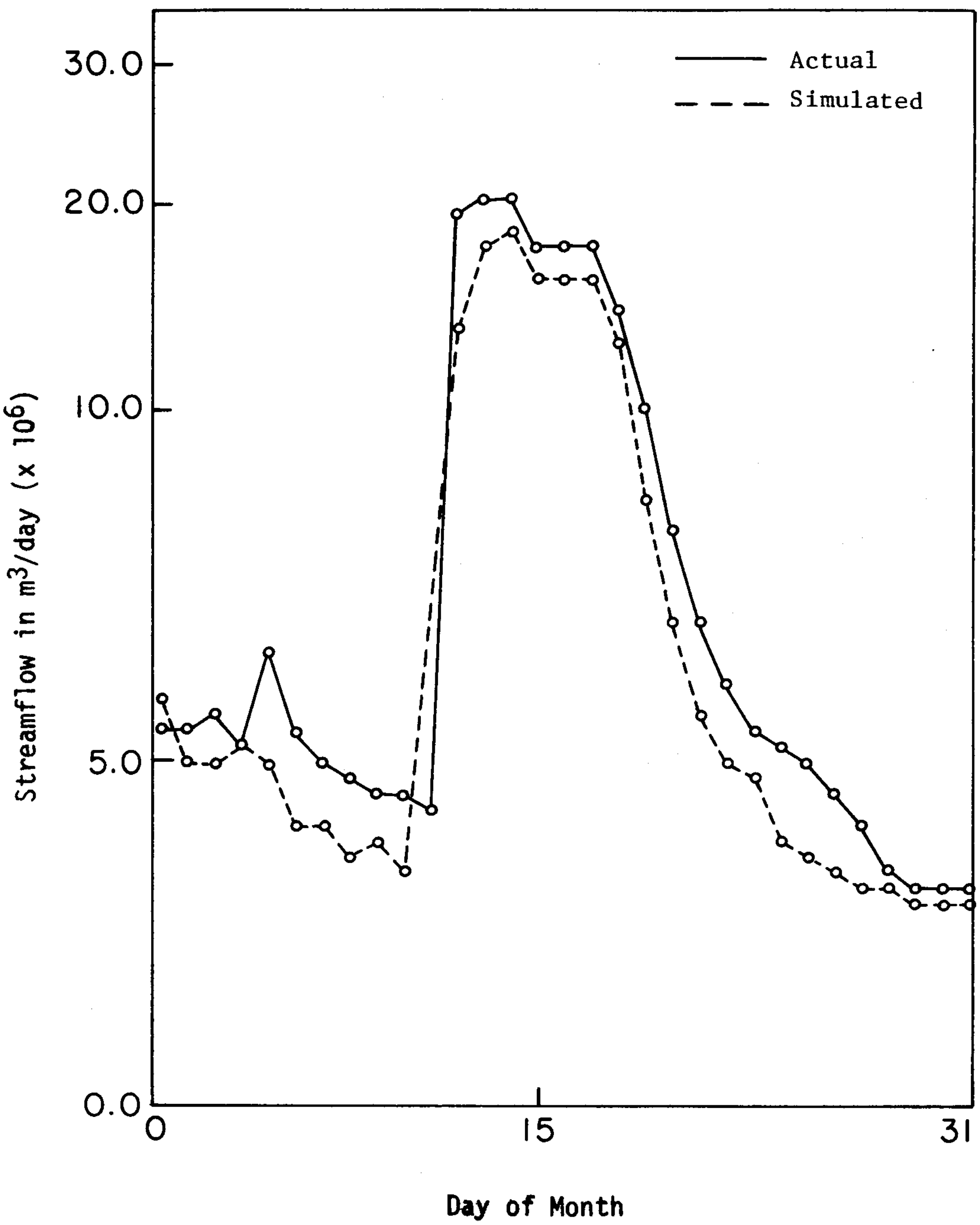

Figure 15d. Observed and Predicted Flows for the Toutle River Using the Modified CLS Model with Square Root Transformation in Prediction Mode, January, 1980

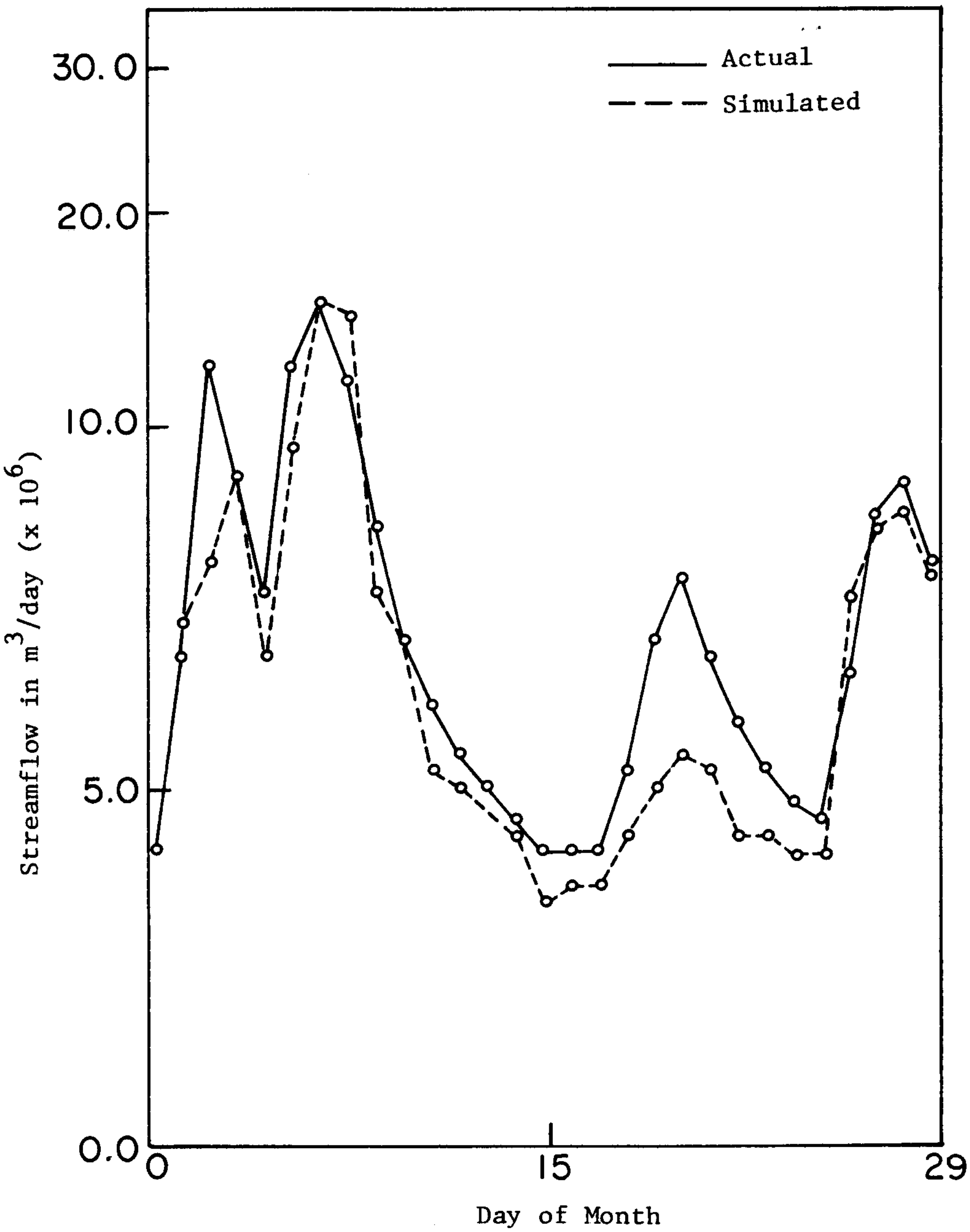

Figure 15e. Observed and Predicted Flows for the Toutle River Using the Modified CLS Model with Square Root Transformation in Prediction Mode, February 1980

Table 9. Comparison of Consistency of Prediction Errors for Transformed and Untransformed Models

Prediction Mode With Square Root Transformation Water Year 1977		Prediction Mode Without Square Root Transformation Water Year 1977	
Description	Value	Description	Value
Determination Coefficient	.8607	Determination Coefficient	.5741
Standard deviation of residuals	.0374	Standard deviation of residuals	.0432
Water Year 1978		Water Year 1978	
Determination coefficient	.9104	Determination coefficient	.0592
Standard deviation of residuals	.0531	Standard deviation of residuals	.0592

Comparison with a Conceptual Deterministic Model

The simulated runoff from the National Weather Service (NWS) model (Peck et al., 1976) was compared with results of simulations using the modified CLS model for the Toutle River. Some of the comparisons are described in Tables 10 and 11. Because the calibration process in the NWS model is not statistical but conceptual, this comparison is limited to some physical aspects of the simulation rather than statistical aspects.

Table 10. Comparison of NWS and Modified CLS Model for the Toutle River for Water Years 1973-1976

Month	1973 Percent* Difference	1973 Yearly Abs. Av. Error	1974 Percent Difference	1974 Yearly Abs. Av. Error	1975 Percent Difference	1975 Yearly Abs. Av. Error	1976 Percent Difference	1976 Yearly Abs. Av. Error
NWS Model								
Oct	-30.0		-38.0		-22.0		-61.0	
Nov	-27.0		- 6.0		7.0		12.0	
Dec	-25.0		17.0		17.0		6.0	
Jan	- 2.0		6.0		- 2.0		- 2.0	
Feb	21.0	26.5	48.0	25.0	20.0	22.4	21.0	25.5
Mar	- 2.0		17.0		10.0		40.0	
Apr	29.0		13.0		6.0		59.0	
May	32.0		-10.0		-12.0		5.0	
Jun	6.0		-37.0		-17.0		31.0	
Jul	-62.0		-42.0		-46.0		-44.0	
Aug	-57.0		-46.0		-56.0		-38.0	
Sep	-25.0		-20.0		-54.0		-35.0	
Modified CLS Model								
Oct	- 6.0		67.0		10.0		45.0	
Nov	5.0		16.0		71.0		- 3.0	
Dec	16.0		- 6.0		- 3.0		- 8.0	
Jan	-15.0		-13.0		- 4.0		-10.0	
Feb	10.0		- 9.0		-13.0		3.0	
Mar	-13.0	19.3	-17.0	16.5	5.0	22.9	- 3.0	19.2
Apr	- 3.0		-16.0		9.0		-11.0	
May	7.0		-27.0		-18.0		-20.0	
Jun	22.0		- 4.0		6.0		5.0	
Jul	42.0		1.0		4.0		13.0	
Aug	26.0		-13.0		59.0		50.0	
Sep	67.0		10.0		73.0		60.0	

* Percent deviation of simulated volume from actual volume

Table 11. Annual Error Summary for Application of NWS and Modified CLS Model to the Toutle River

NWS Model		Modified CLS	
Water Year	Percent Difference	Water Year	Percent Difference
1973	-1.8	1973	6.8
1974	3.0	1974	-6.5
1975	2.1	1975	5.0
1976	9.1	1976	-0.9

Summary

The results and comparisons presented above do not demonstrate conclusively the superiority of the new model being proposed nor are the comparisons necessarily applicable in general. However, the results do suggest the potential usefulness of the simplified model for operational studies. The concept utilized is simple and is based on the estimation of a single response function relating effective precipitation to runoff. The assumptions are approximate, and may require further refinement for shorter time steps (e.g., on the order of one hour). However, for daily time scales the concern is generally with total volumes rather than the exact rates at which the quantities are transferred from one catchment unit to another, and in this case, the rainfall preprocessor seems to work well.

It should also be noted that the computation of the impulse responses to the effective inputs to the system by the CLS model, can eliminate some of the inaccuracies and biases in the conceptual part of the model. The preprocessing part of the model essentially accommodates time variance and nonlinearities of the catchment response into the runoff simulation.

The results clearly demonstrate that at least in the examples provided, the simplified model is comparable to the more sophisticated National Weather Service conceptual model based on physics. Also, the modified CLS model overcomes some of the limitations of the original CLS model. It is capable of simulating the recession part of the hydrograph, which the original CLS model based on API values did not simulate properly in the example. Also, the performance of the new model for long dry periods followed by a few days of heavy rainfall is far better than that of the original model.

It was also demonstrated that the new model, when used with a square root transformation, performs better by decreasing the tendency of the model to fit the higher runoff values rather than the low ones. This transformation also results in more consistent determination coefficients for years of low and high flows when the model is used in a prediction mode. This aspect may be significant when the change of response of the catchment to a given amount of precipitation is to be assessed on a statistical basis.

CHAPTER V

IMPLEMENTATION OF THE NWS (RUNOFF) AND THE MODIFIED CLS MODEL TO CRAB CREEK

Characteristics of the Basin

As discussed before, implementation of a precipitation-runoff model to Eastern Washington catchments has many inherent problems. First, the rainfall is far less than the evaporation demand and second, most of the streams are affected by substantial irrigation and other withdrawals. Based on the second consideration, Crab Creek was chosen because of its proximity to the area most affected by the May 18, 1980 ashfall. However, the best calibration obtained for both the NWS and the modified CLS model was far from satisfactory. The basin boundary is shown in Figure 16 and some of the basin characteristics are given in Table 12. These characteristics give an idea of the possible limitations to the modeling efforts.

Table 12. Some Basin Characteristics for Crab Creek

Drainage area (mi^2)	1042
Yearly Evaporation Demand (inches)	42
Mean Annual Precipitation (inches)	10
Mean Annual Discharge (ft^3/sec)	75
Maximum Discharge (ft^3/sec) (for period of record)	8370
Minimum Discharge (ft^3/sec)	0 (for several days at a stretch)

Figures 17 and 18 show the recorded runoff and the recorded precipitation for the months of December and January, and demonstrates the eratic response of the catchment to incident precipitation. As seen from Figures 17 and 18,

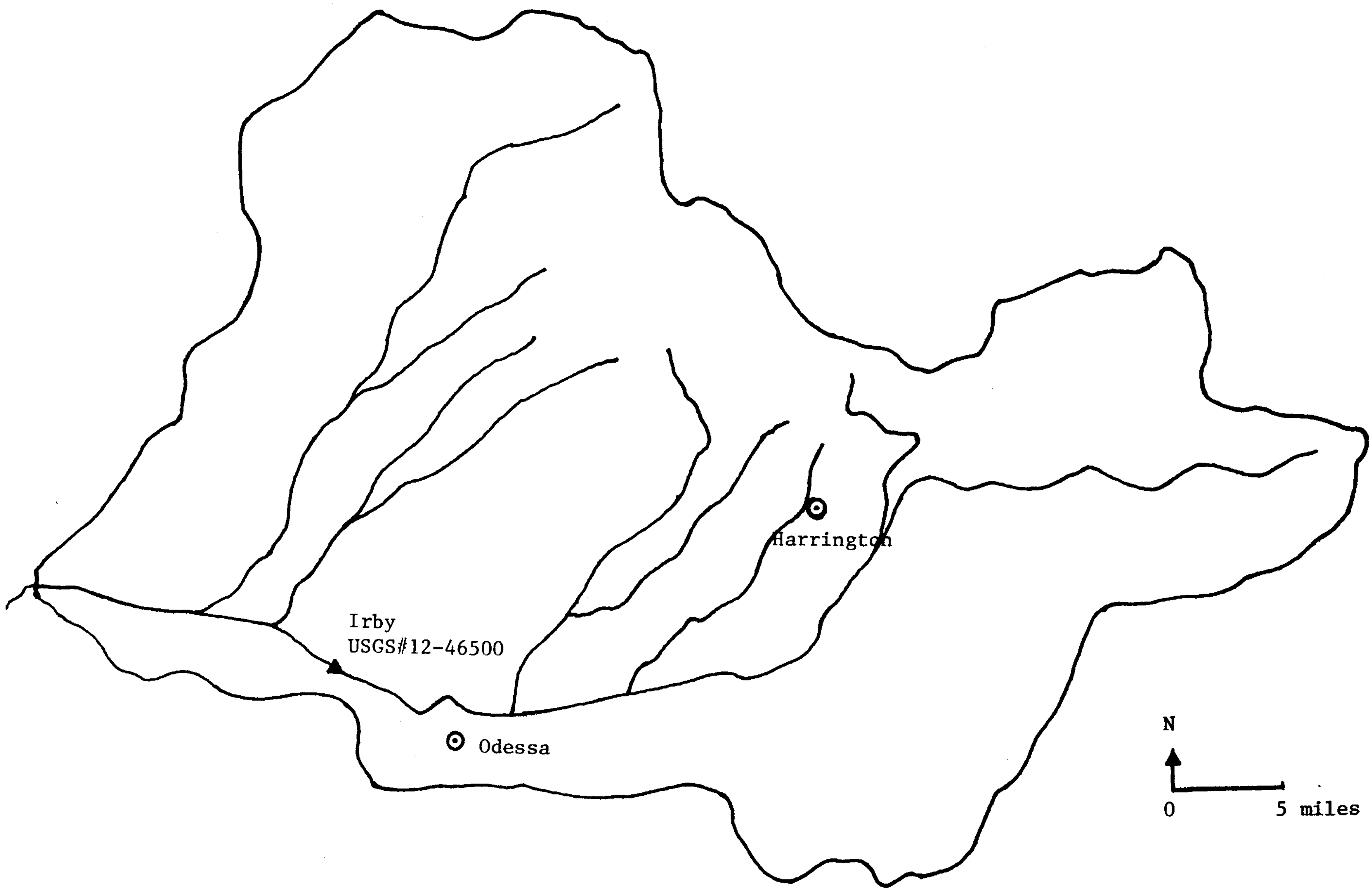

Figure 16. Crab Creek Catchment Area

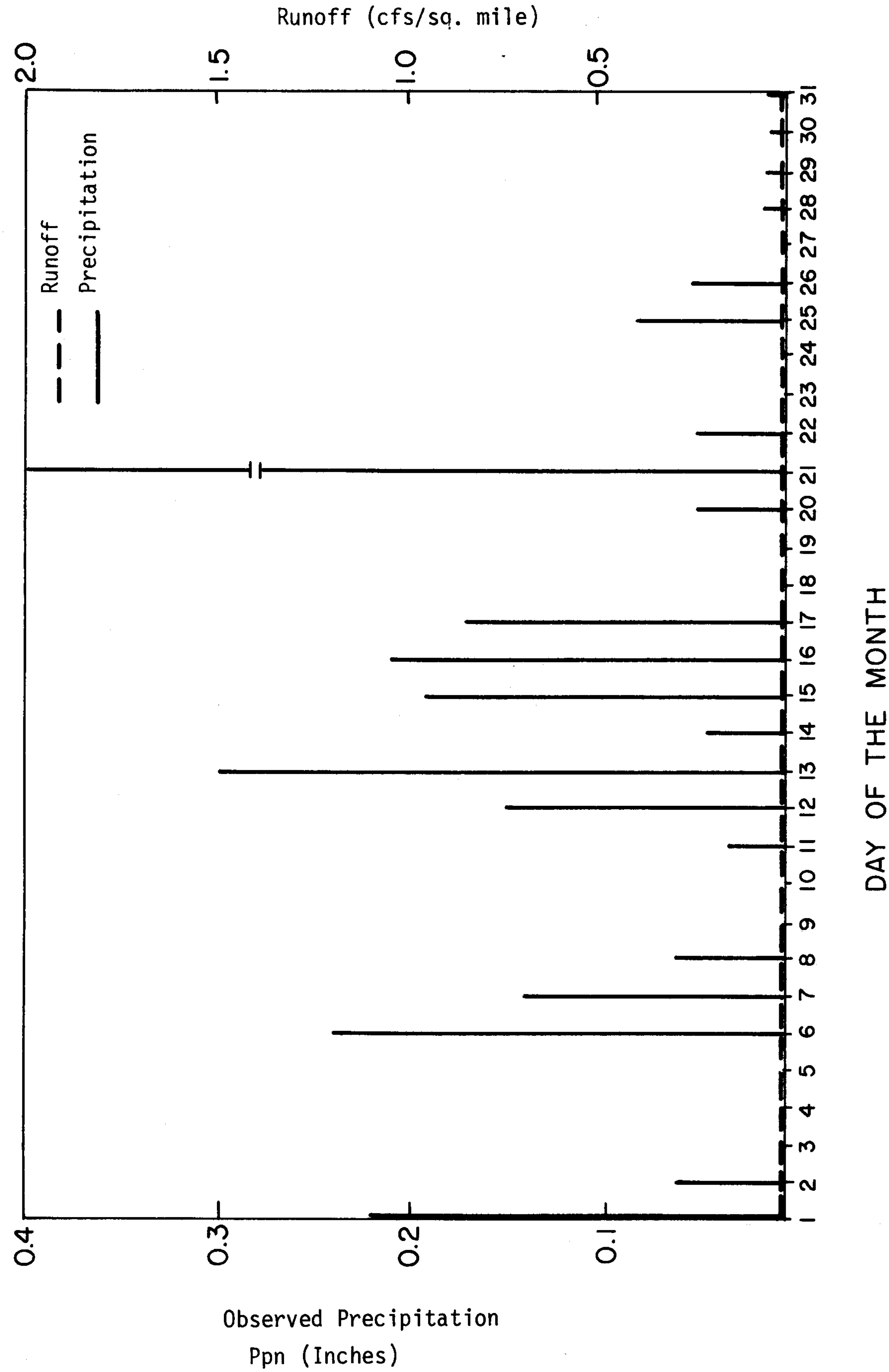

Figure 17. Observed Precipitation vs. Runoff for Crab Creek, December 1973

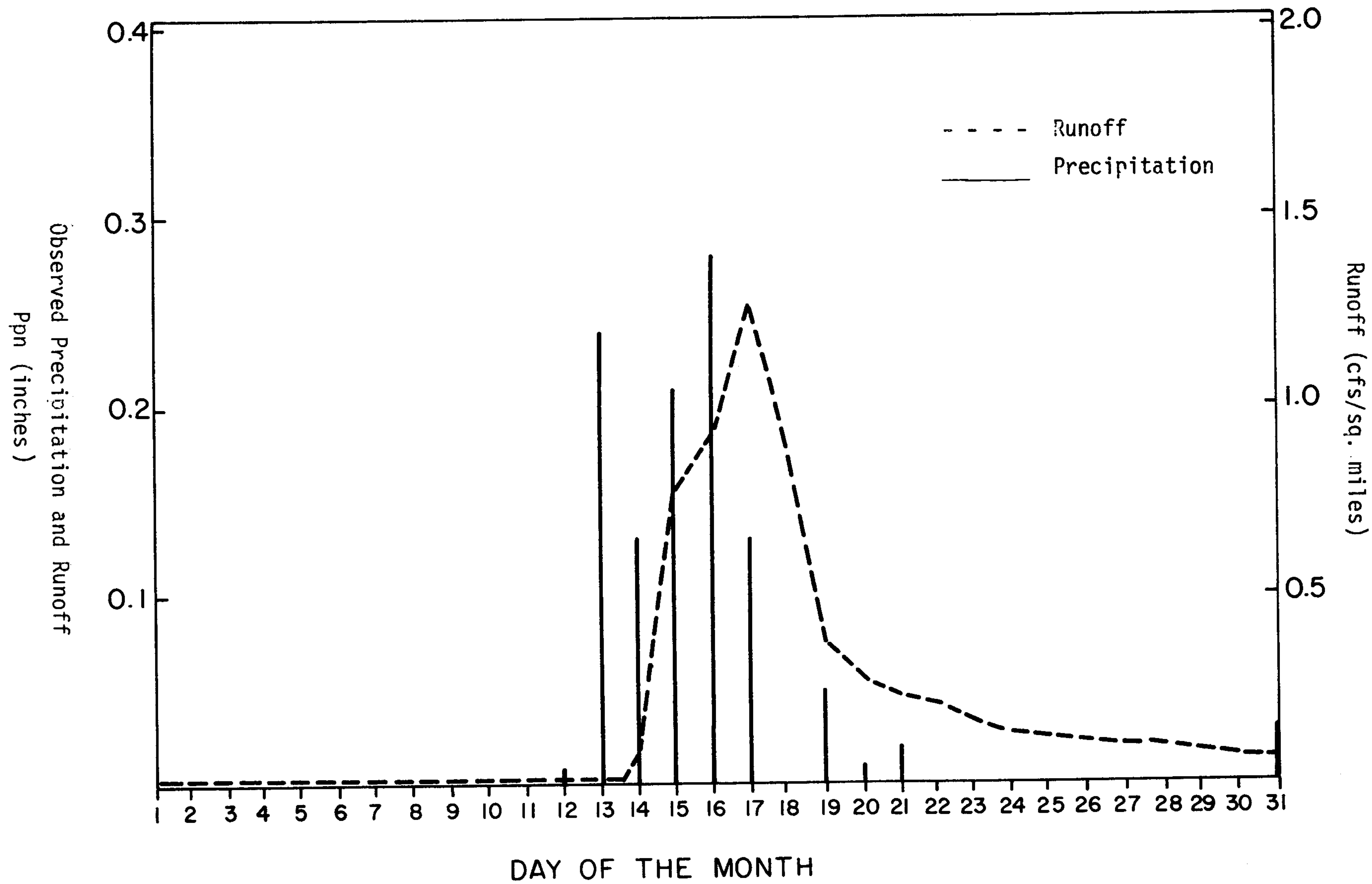

Figure 18. Observed Precipitation vs. Runoff for Crab Creek, January 1973

even for relatively high amounts of precipitation in the high flow months like December, there was virtually no runoff for December, 1973, while for a similar period like January, 1973, a smaller amount of precipitation for a shorter period induced appreciable runoff. These types of anomalous behavior, and the high evaporation demand, complicate the calibration process. Also, the recorded runoff was essentially a series of spikes on a very small number of days, and for other days the recorded runoff was negligible. Both the modified CLS model and NWS runoff model failed to simulate this behavior.

Another problem was the large size of the catchment, and the existence of only two meteorological stations (Odessa and Harrington) in the vicinity. The precipitation recorded at these two stations differ appreciably as seen from Table 13. For example, in the period from October 1974 to February 1975, Odessa shows higher precipitation, whereas in the period from March 1975 to September 1975, Harrington shows appreciably higher precipitation. Although a weighted average of these stations could be used to drive the runoff simulation models, it was found that Odessa alone gave better results.

Table 13. Precipitation at Odessa and Harrington for Water Year 1975

Months	Precipitation at Odessa (inches)	Precipitation at Harrington (inches)
October	0.01	0.0
November	1.92	2.52
December	1.42	1.52
January	1.11	0.43
February	1.60	1.07
Total	6.06	5.54
March	1.33	3.34
April	1.36	1.81
May	0.84	1.41
June	0.60	0.69
July	0.67	1.59
August	0.74	0.70
September	0.0	0.0
Total	5.54	9.54

Some simple computations demonstrate that most of the runoff can be attributed to direct precipitation on the stream channel and a small area adjacent to the channel, and that most of the catchment contributes insignificantly. The exception is during periods of high flow, when it is necessary to consider a larger contributing area. Tables 14 and 15 show some of the parameters for the NWS model for the two best possible calibrations.

Table 14. Calibration Coefficients and Evapotranspiration Data for Crab Creek Drainage Above USGS Gauge 12-4650 (Calibration (A)

Drainage Area = 1,042 square miles

Model Parameters:

	UZTW	UZFW	ZTW	LZFWS	LZFWP
Capacity [(a)]	1.50	1.00	2.00	3.00	3.00
Initial Contents [(a)] (Oct. 1972)	0.00	0.00	0.01	0.00	0.01

UZ-K	LZS-K	LZP-K	ZPERC	REXP
0.40	0.020	0.0090	20.0	1.80

SIDE	SSOUT	PCTIM	SARVA	RSERV
0.0	0.0	0.00	0.010	0.30

PBASE	ADIMP	ADIMC	PFREE
0.087	0.030	0.010	0.200

Mean Daily Potential Pan Evaporation[a]

OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP
.13	.70	.40	.03	.05	.09	.16	.23	.32	.37	.31	.21

[a]inches of water

Table 15. Calibration Coefficients and Evapotranspiration Data for Crab Creek Drainage Above USGS Gauge 12-4650 (Calibration (B)

Drainage Area = 1,042 square miles

Model Parameters:

	UZTW	UZFW	LZTW	LZFWS	LZFWP
Capacity[(a)]	0.15	0.25	2.00	3.00	3.00
Initial Content[(a)] (Oct. 1972)	0.00	0.00	0.01	0.00	0.01

UZ-K	LZ-K	LZP-K	ZPERC	REXP
0.40	0.20	0.009	20.0	1.80

SIDE	SSOUT	PCTIM	SARVA	RSERV
0.00	0.00	0.000	0.010	0.30

PBASE	ADIMP	ADIMC	PFREE
0.087	0.030	0.010	0.200

Mean Daily Potential Pan Evaporation[a]

OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP
.13	.70	.40	.03	.05	.09	.16	.23	.32	.37	.31	.21

[a]inches of water

The NWS Soil Moisture Accounting Model

The Sacramento model structure, described in Burnash et al. (1973) is schematized in Peck (1976). The relevant figures from this publication are reproduced in Figures 19 and 20, respectively. All the variables in Figure 19 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,

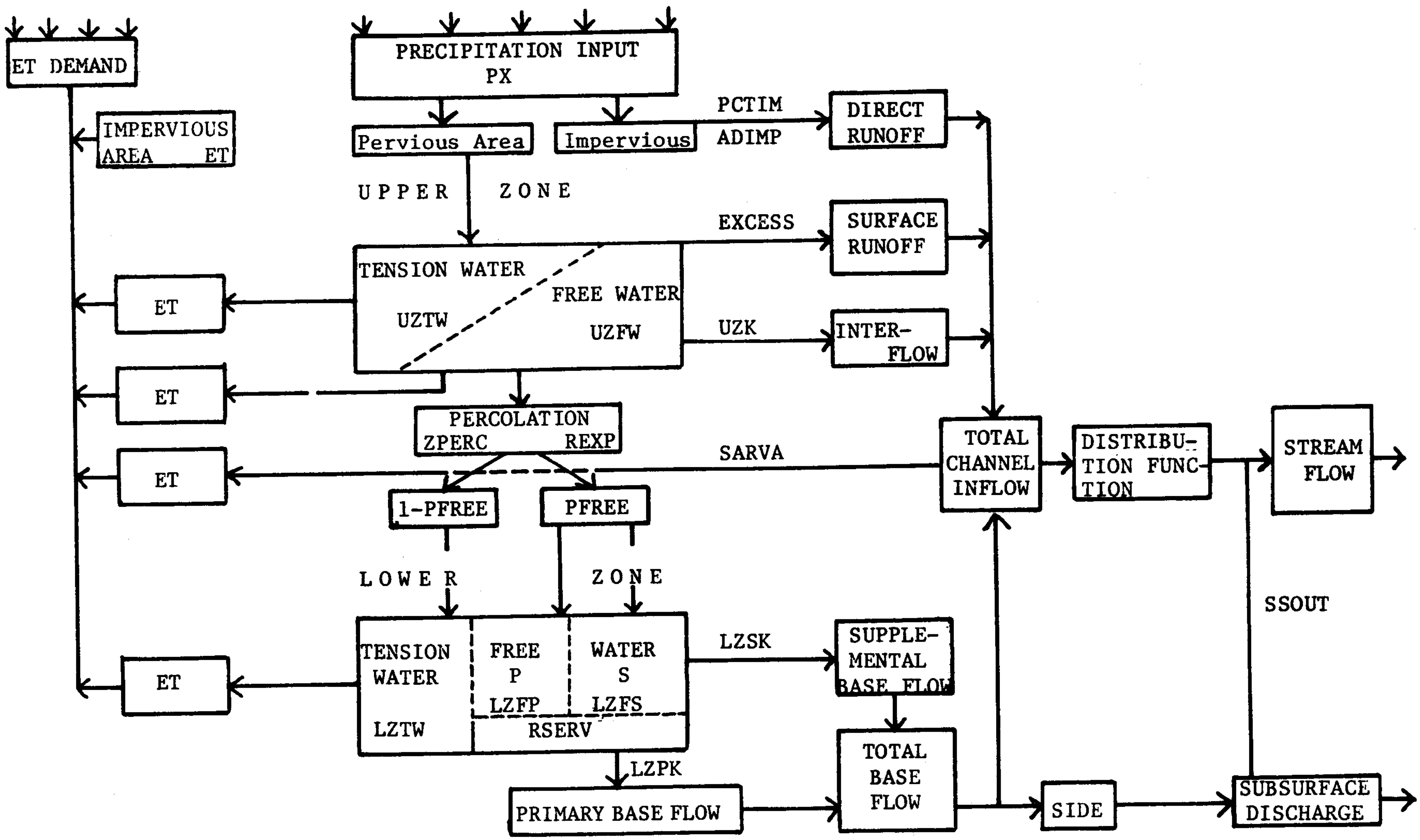

Figure 19. Schematic of National Weather Service River Forecast Soil Moisture Accounting (Sacramento) Model (Fig. 1 from Peck, 1976)

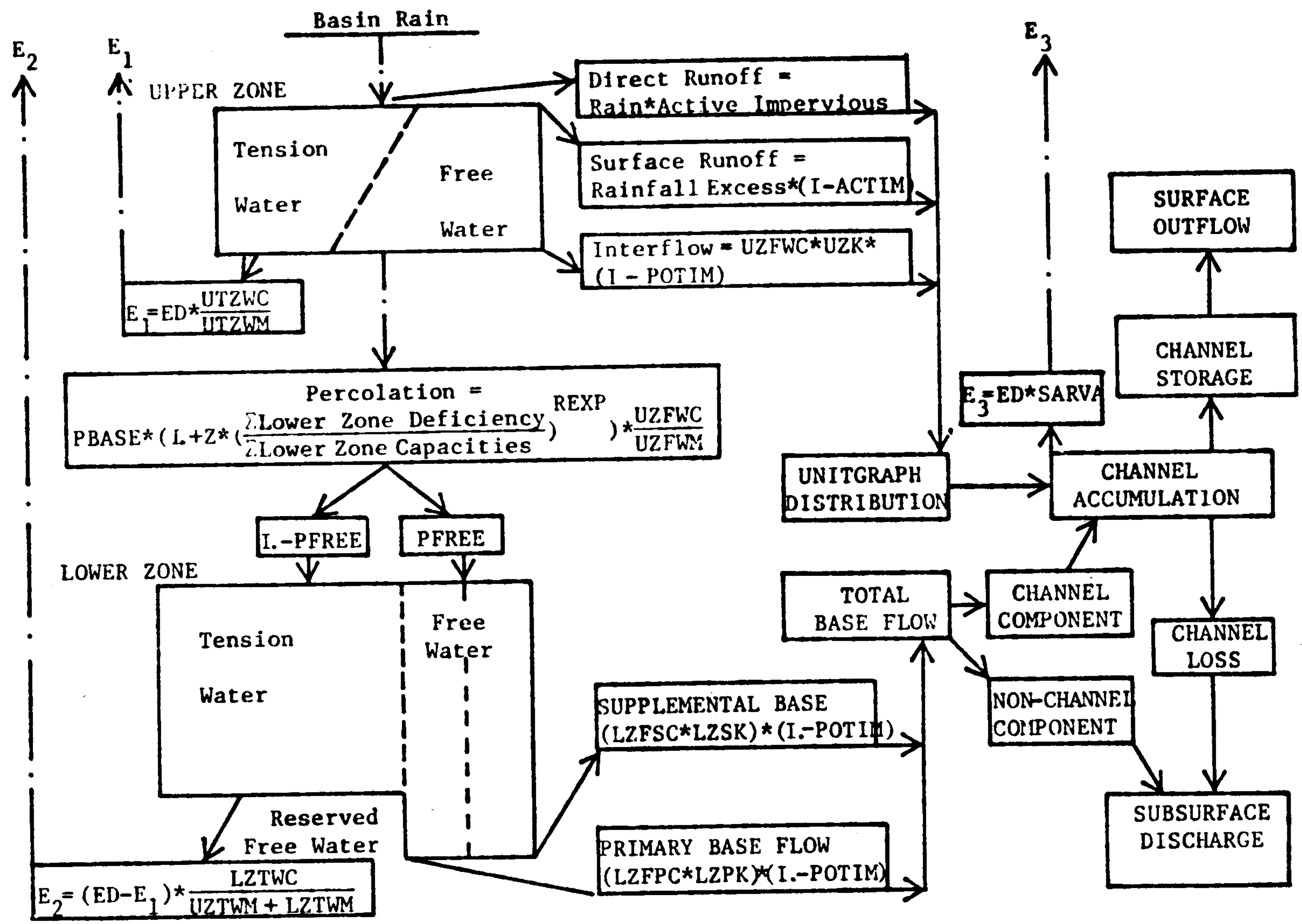

Figure 20. Functional Relationships Used in the Sacremento Model

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 gauge 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 precedure that may be used to adjust parameters, however, this was found to be quite expensive and sometimes unreliable, so manual calibration was used instead.

The above procedure is used when the catchment is modeled as a single contributing area. Clearly, where orographic effects are experienced and/or more than one precipitation station are available, the catchment should be divided into several subcatchments.

The major components of the model are shown in Figure 20. 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 runoff. The pervious fraction (most of Figure 20) 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 in short-term catchment response to precipitation. The lower zone contains a tension water zone (water can be removed only by infiltration) 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.

Application of NWS Model to Crab Creek

As is evident from Tables 14 and 15 the major difference between Calibrations (A) and (B) was that the storage capacity of the upper zone free water storage was 1.0 inches in (A) and only 0.25 inches in (B). This variation was specified in order to find any significant sensitivity of the simulated flow to this parameter, which is important for the computation of interflow. With a high capacity, the period required to fill and drain is prolonged, so that if the simulated peaks are too high compared to the recorded, and the simulated recession is decaying faster than recorded, an increase in this parameter (UZFWM) may correct the problem. Also, the upper zone tension water content specified in Model (A) was 1.50 inches while in Model (B) it was only 0.15 inches. Both of these values are far less than the potential evaporation demand and therefore from a physical standpoint are unrealistic. However, given the annual mean precipitation of about 10 inches water balance considerations dictate that these values are plausible. In any event, as shown by Figures 21 to 24, representing some of the simulated hydrographs by both these models, the changes effected were negligible for the calibration period October 1972 to September 1975.

It is clear from Figures 21 to 24 that the calibrations obtained were not satisfactory. While for months like January 1973, the simulated hydrograph showed much smaller flows than recorded, the simulated flows for months like December 1973 were much higher than the recorded, for both calibrations. This problem could not be corrected.

An attempt was also made to implement the modified CLS model for this catchment. However, even after incorporating both precipitation and tempera-

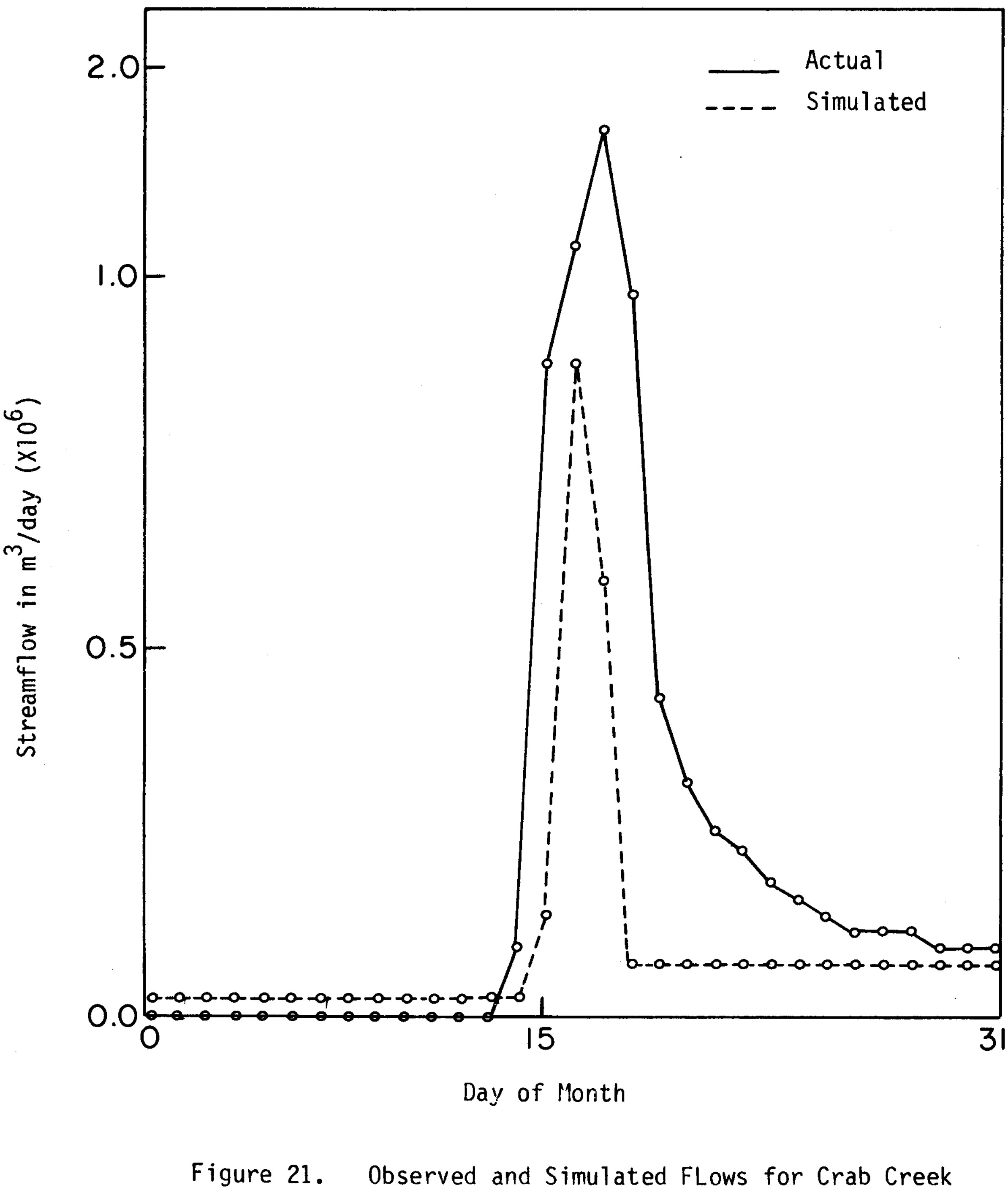

Figure 21. Observed and Simulated FLows for Crab Creek Using the NWS Model for January 1973 (Calibration A)

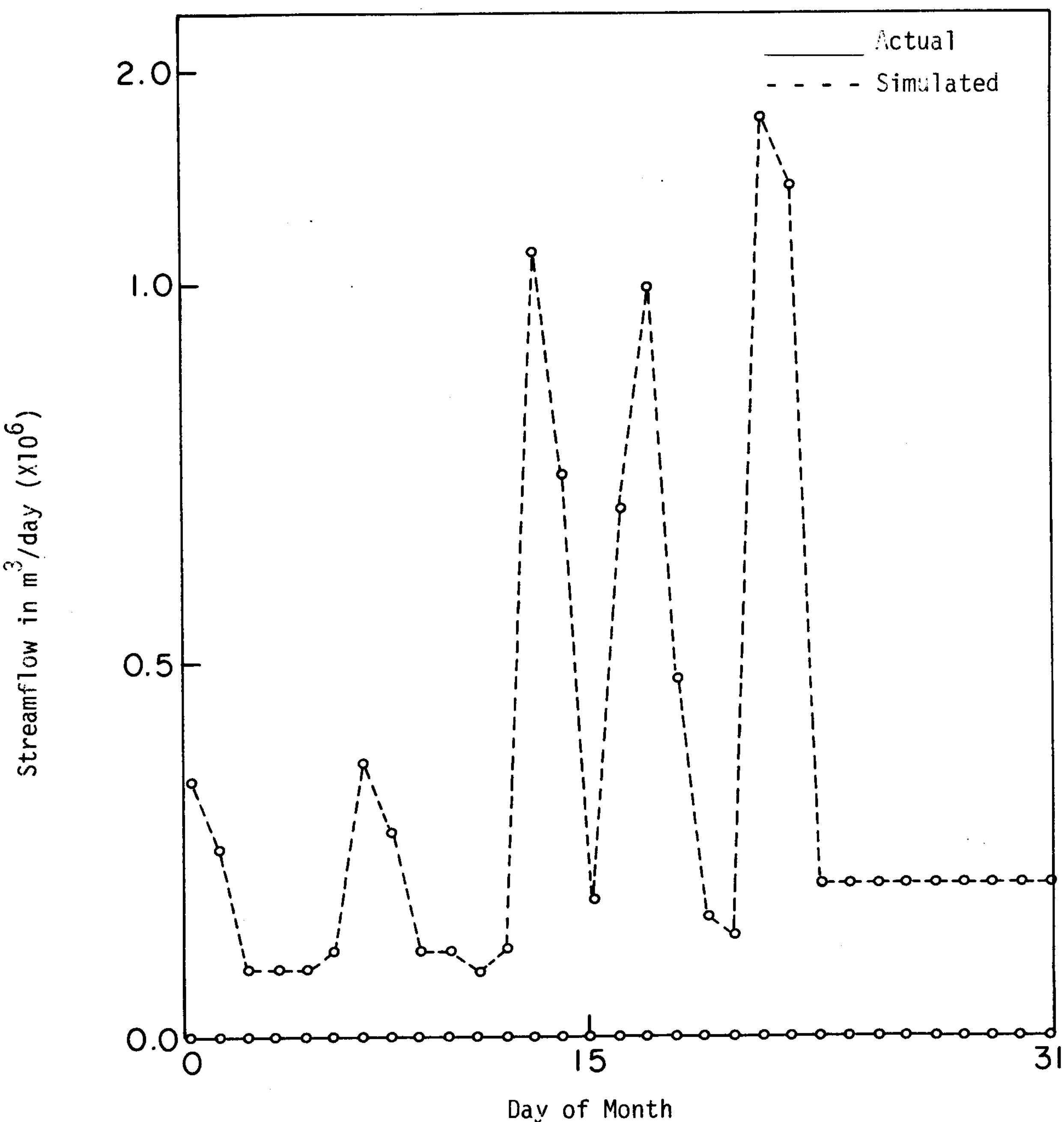

Figure 22. Observed and Simulated Flows for Crab Creek Using the NWS Model for December 1973 (Calibration A)

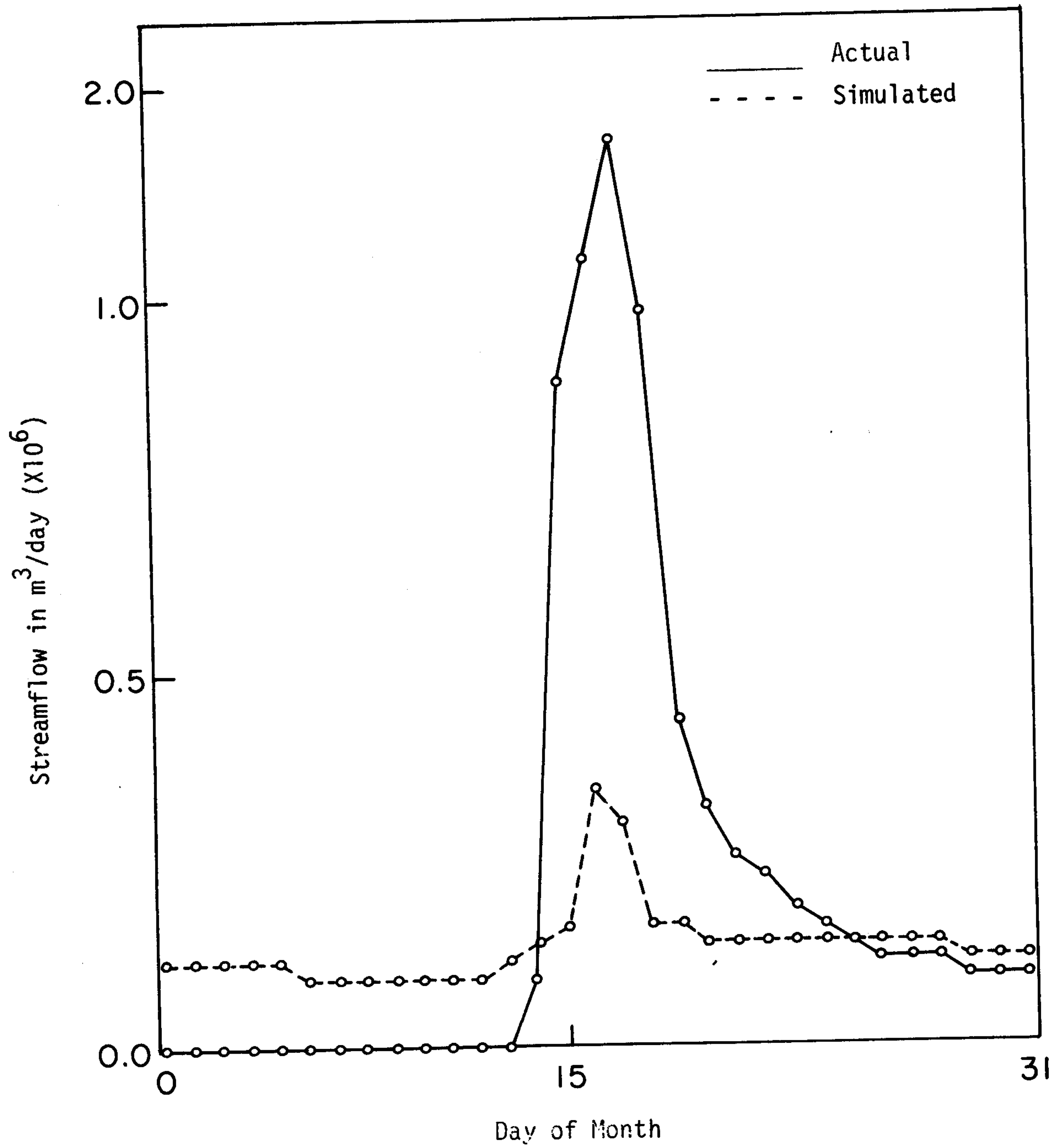

Figure 23. Observed and Simulated FLows for Crab Creek Using the NWS Model for January 1973 (Calibration B)

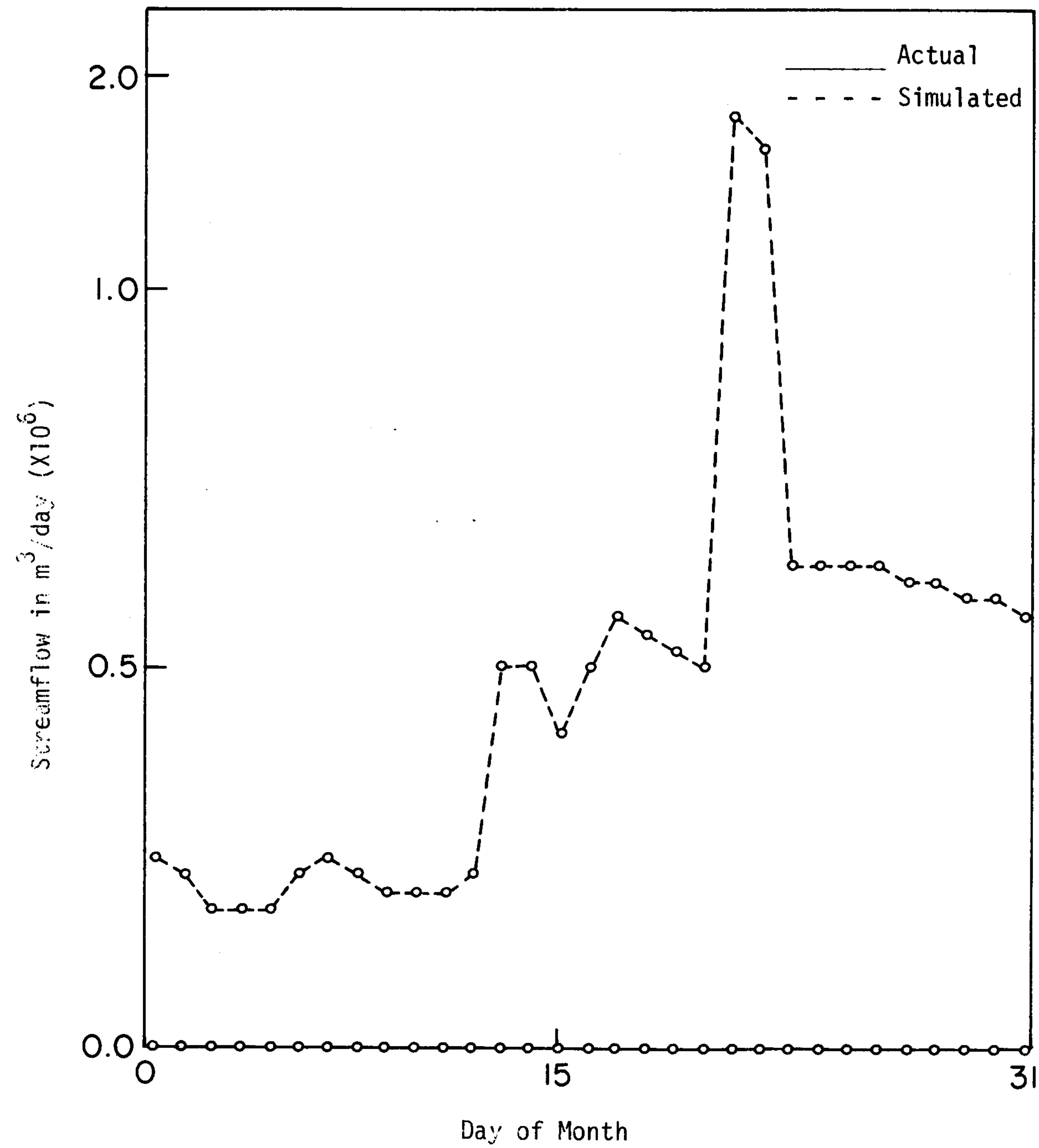

Figure 24. Observed and Simulated Flows for Crab Creek Using the NWS Model for December 1976 (Calibration B)

ture recording stations, acceptable calibration could not be obtained. The recession flows could be properly simulated and the timing of the simulated peaks matched the recorded peaks, however the peak flow magnitudes could not be simulated. Attempts to make further calibrations proved fruitless. It was ultimately determined that it would be futile to attempt post-eruption simulations with such a poor calibration, and the planned assessment of post-eruption changes in this basin was abandoned.

CHAPTER VI

ANALYSIS OF RESULTS

As stated earlier, the calibration of the modified CLS model for the Toutle River was statistically and visually acceptable, given the range of accuracy and limitations of the data used. The consistency of the model predictions was also satisfactory when this model was calibrated for a given period (October 1972 to September 1976) and these calibrated parameters were used to simulate the daily runoff continuously for a verification period of a few years in length. Within these limitations, it is reasonable to assess the overall changes if any, in the hydrologic response of the catchment following the Mt. St. Helens eruption. The calibration attempts for Crab Creek were not successful, and therefore, no further analysis was undertaken. It is, however, hypothesized that the possible changes that may be expected due to the ashfall in Eastern Washington will not persist due to extensive agricultural use of the land which in effect removes the top soil covering, rendering the impermeable effects of the ash cover insignificant in the long run.

The modified CLS model was calibrated for the period October 1972 to September 1976 for the Toutle basin. The calibrated parameters were then used to simulate the daily runoff for the period including water years 1977 to 1982, given the gross input precipitation. Once the simulated runoff was computed, the errors between the recorded runoff and the simulated runoff were also computed for the entire prediction period of October 1976 to September 1982. Therefore, the prediction period covered more than two years of post-eruption conditions.

Statistical Analysis of Results

The statistical analysis consisted of estimating the errors in prediction (e) given by:

e = (predicted value of streamflow - recorded value of streamflow) for each day

To normalize these errors, $\hat{e}$ was defined as:

$$\hat{e} = \frac{e}{\text{recorded value of streamflow}}$$

Values of $\hat{e}$ were determined for the entire prediction period. To account for the seasonality in these errors, the values of $\hat{e}$ were grouped into 12 different classes each representing a particular calendar month.

The $\hat{e}$ values for a particular month were then ordered on a yearly basis and the probability: $\Pr[\hat{e} \leq E]$, where E is any specified value, were computed. These probabilities were then used to construct the cumulative distribution functions (CDFs) of $\hat{e}$ for each month for the 1977 to 1982 water years. These CDFs are shown in Figures 25 to 36 for the months of January to December.

A trend can be detected from these CDFs for the pre-eruption (May 18, 1980) and post-eruption conditions. It is seen from these figures that for the months from November to March, the error distribution for all the pre-eruption years more or less spans the error distributions obtained for post-eruption conditions. Therefore, it can be concluded that on a daily scale, the overall response of the catchment remains unchanged for these months. This situation is slightly changed for April and May, under post-eruption conditions. The error distribution assumes a slightly positive bias which shows that the predicted volumes under post-eruption conditions, using a pre-eruption calibration may be statistically higher than those predicted in the pre-eruption situation. However, considering the fact that for both these

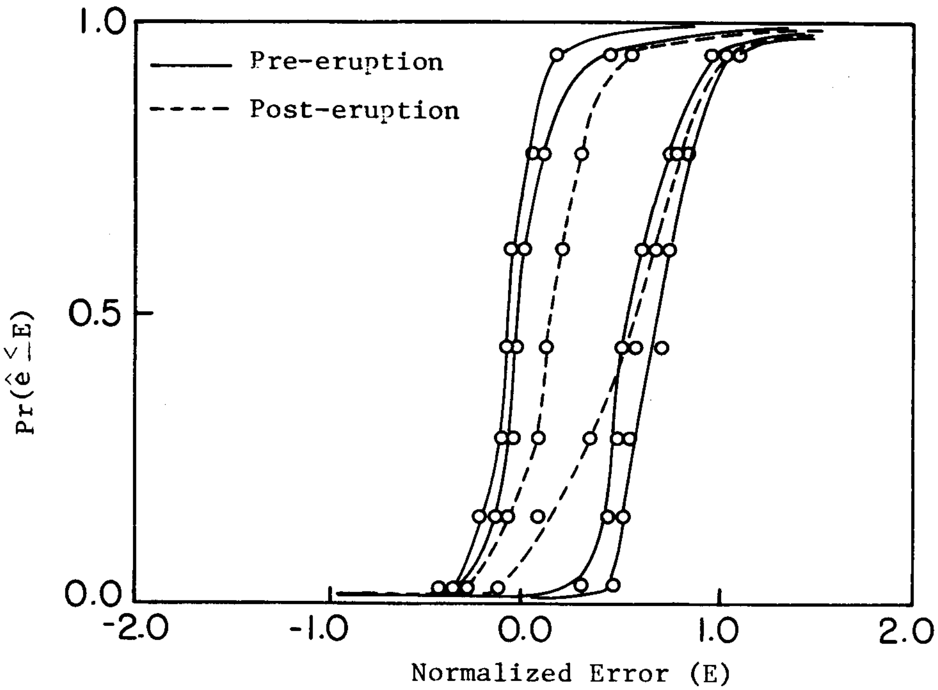

Figure 25. CDFs of Simulation Errors for January (Water Years 1977 - 1982)

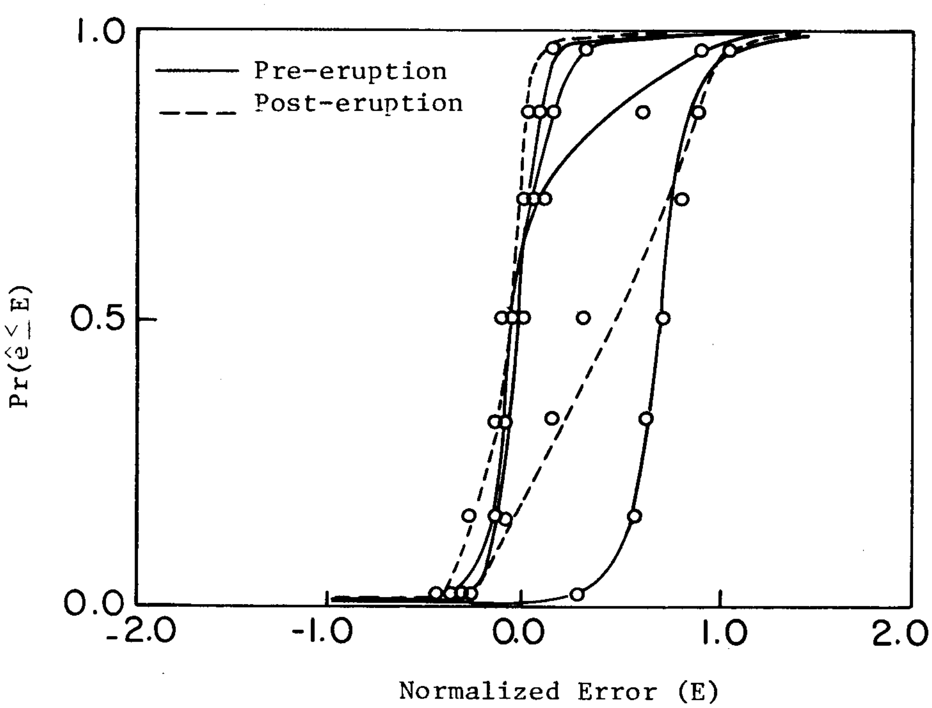

Figure 26. CDFs of Simulation Errors for February (Water Years 1977 - 1982)

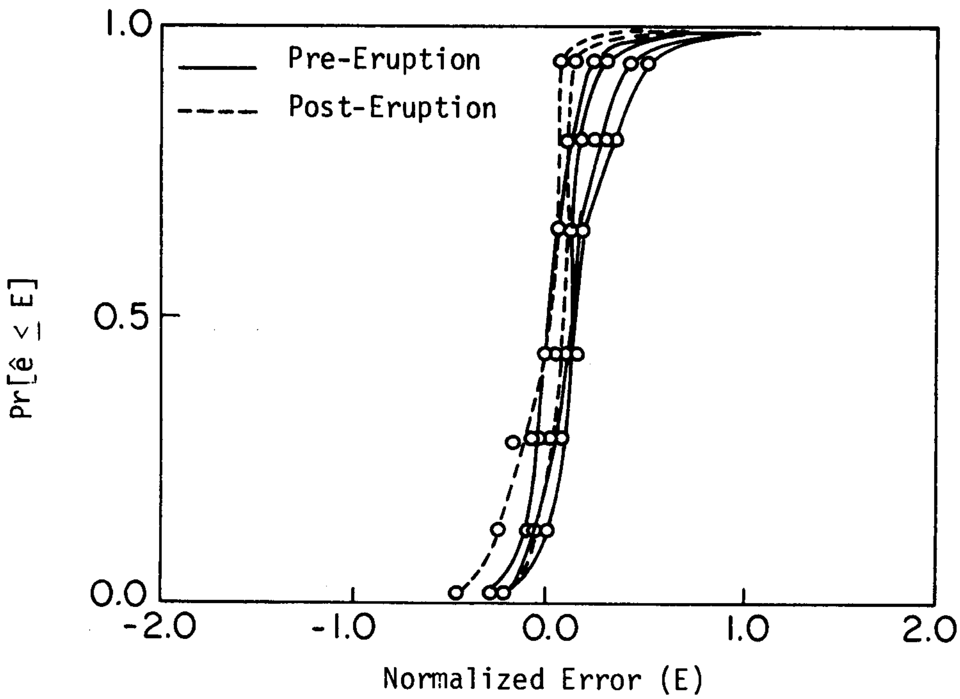

Figure 27. CDFs of Simulation Errors for March (Water Years 1977-1982)

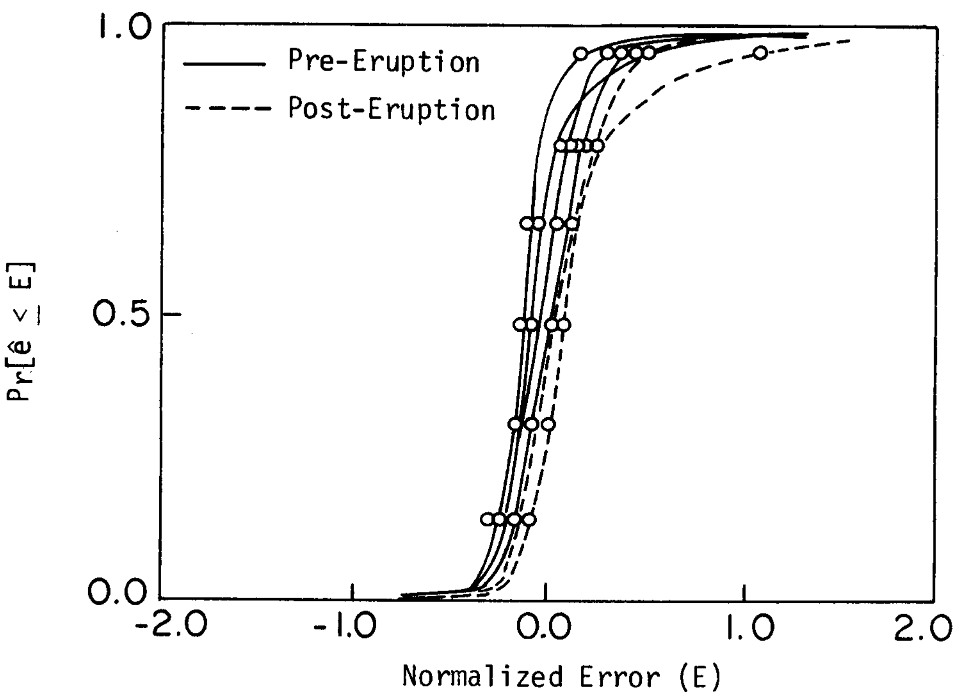

Figure 28. CDFs of Normalized Errors for April (Water Years 1977-1982)

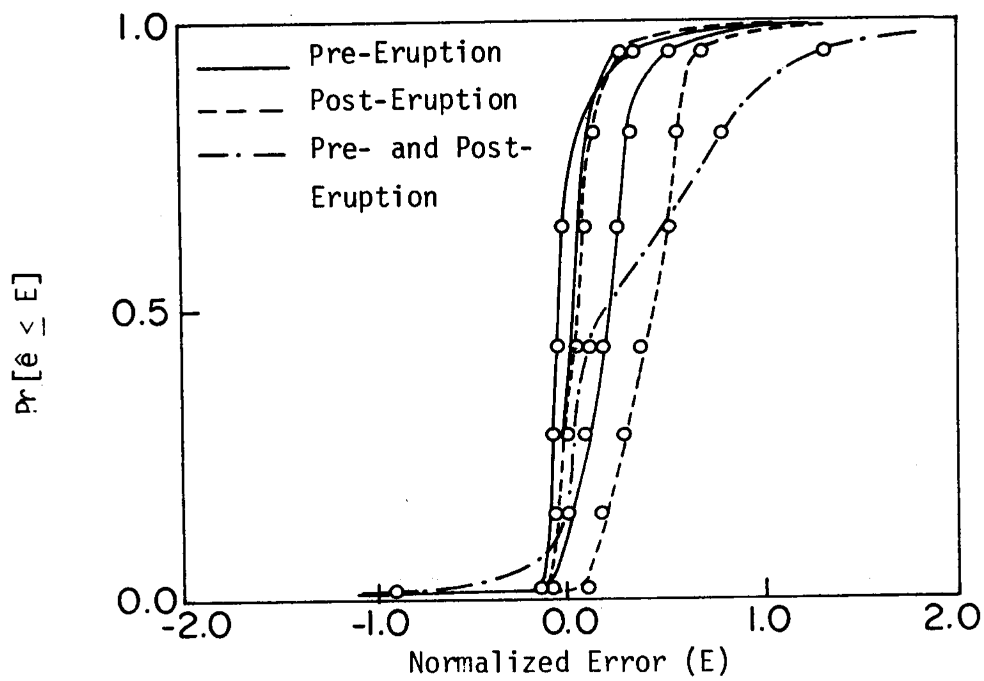

Figure 29. CDFs of Simulation Errors for May
(Water Years 1977-1982)

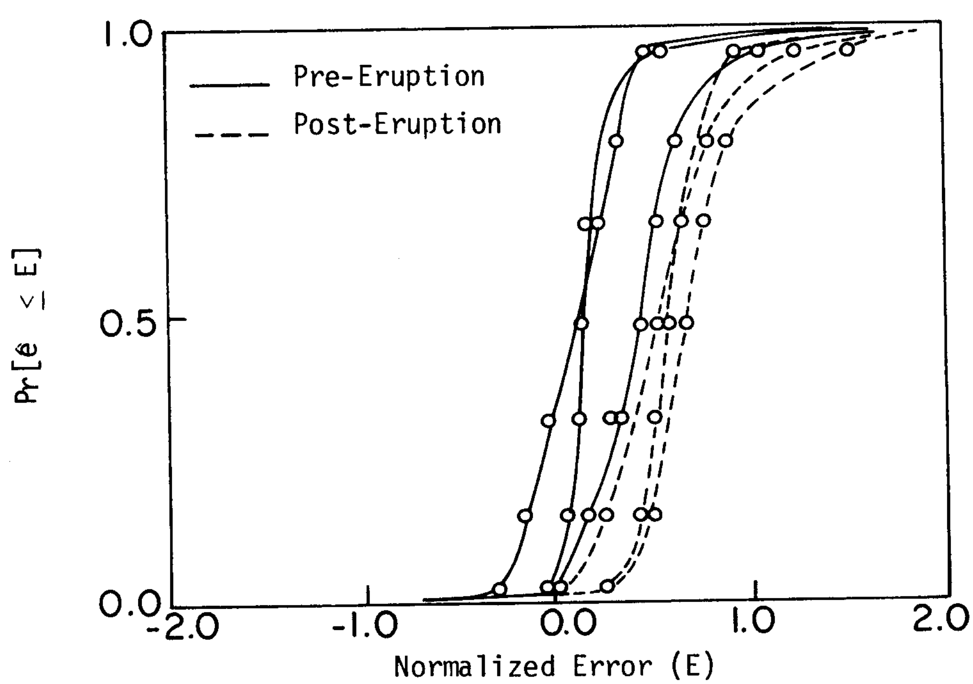

Figure 30. CDFs of Simulation Errors for June
(Water Years 1977-1982)

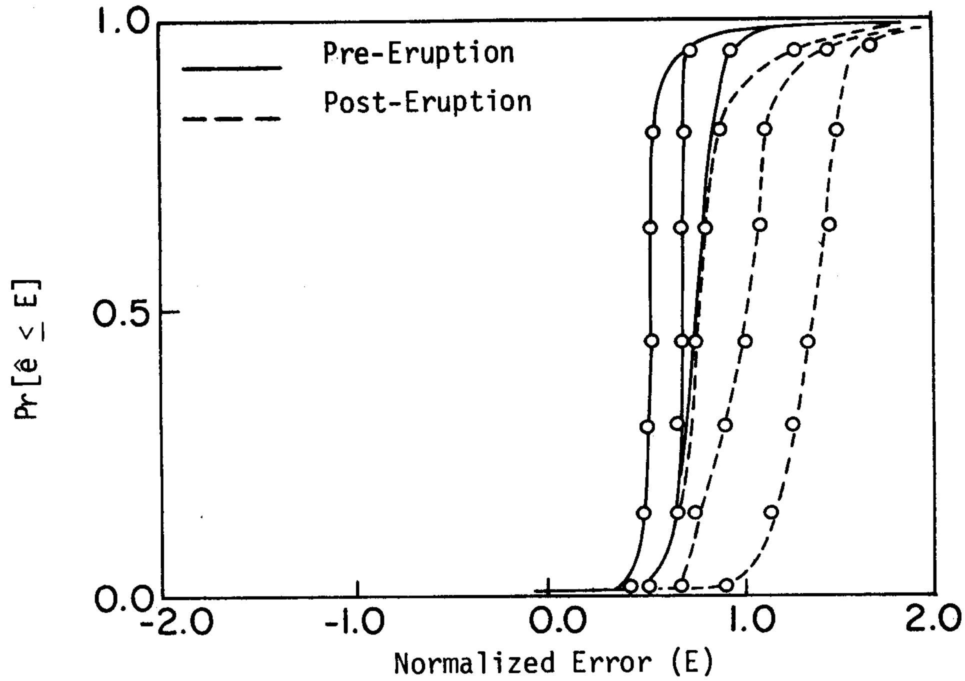

Figure 31. CDFs of Simulation Errors for July
(Water Years 1977-1982)

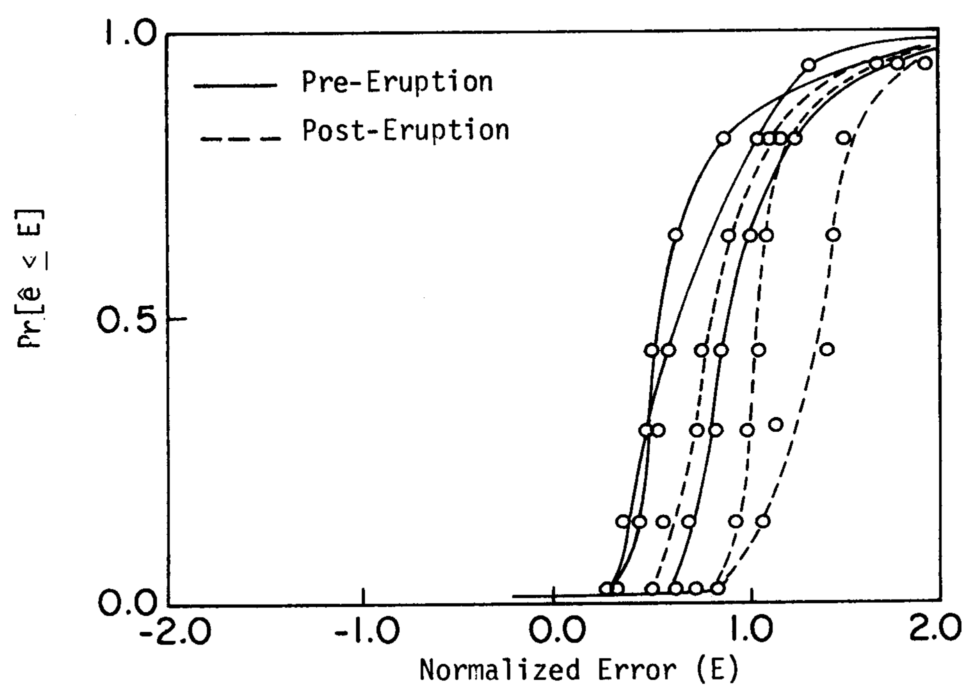

Figure 32. CDFs of Simulation Errors for August
(Water Years 1977-1982)

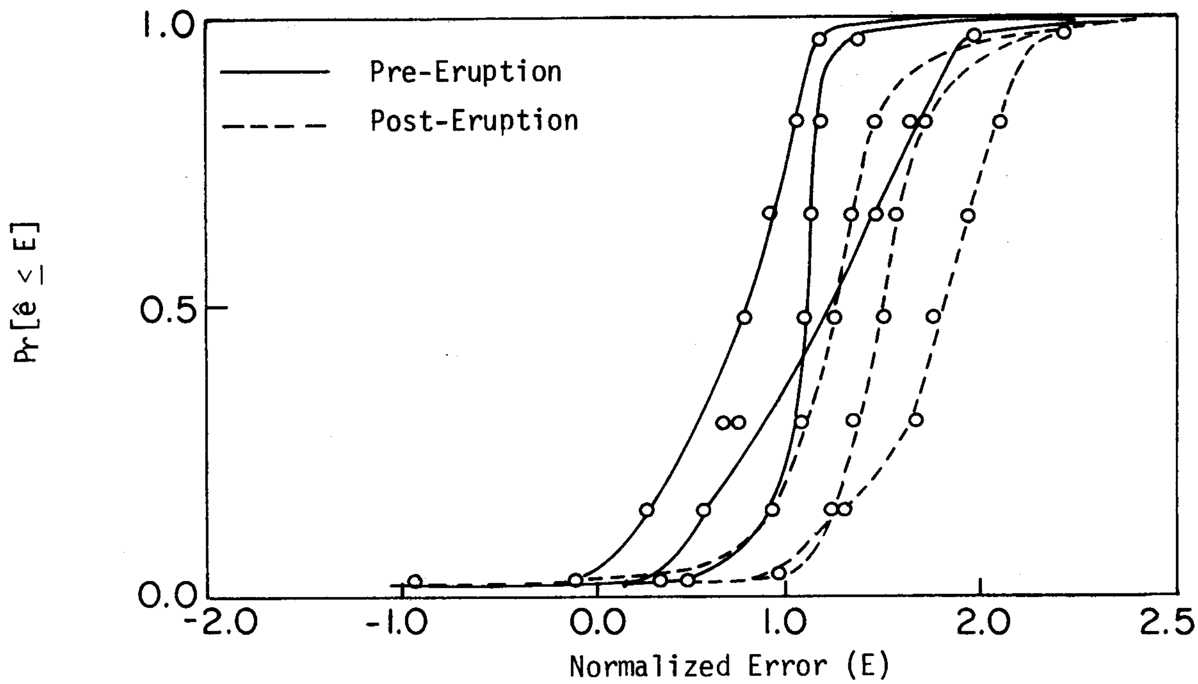

Figure 33. CDFs of Simulation Errors for September (Water Years 1977-1982)

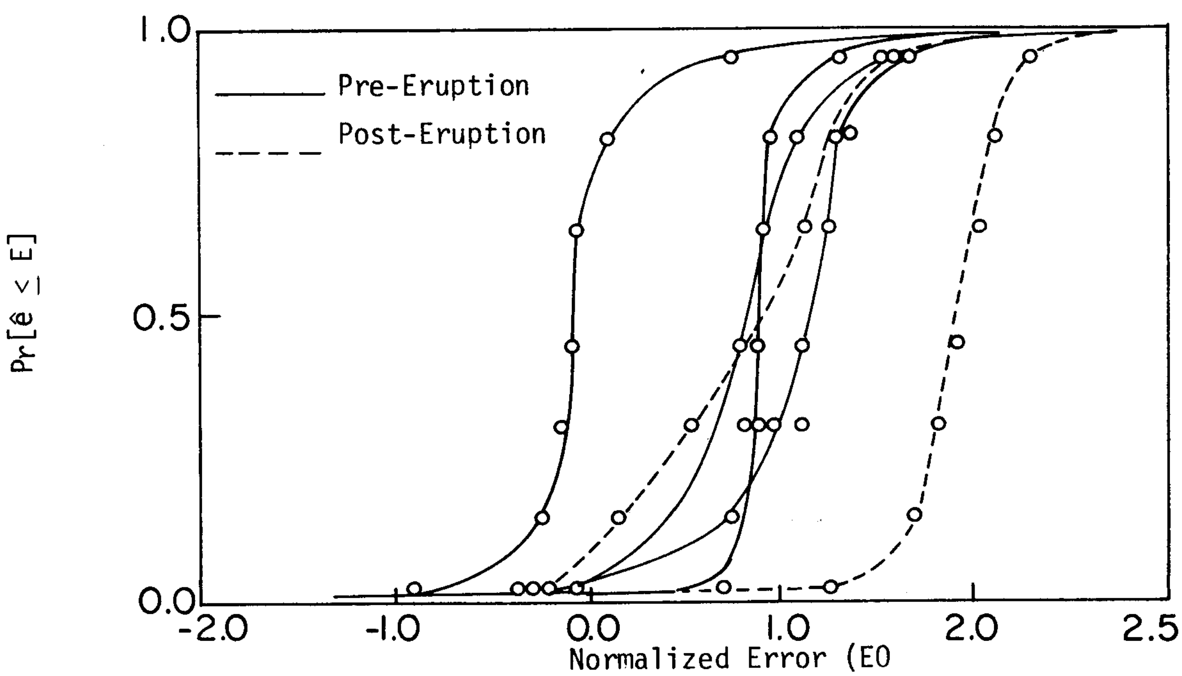

Figure 34. CDFs of Simulation Errors for October (Water Years 1977-1982)

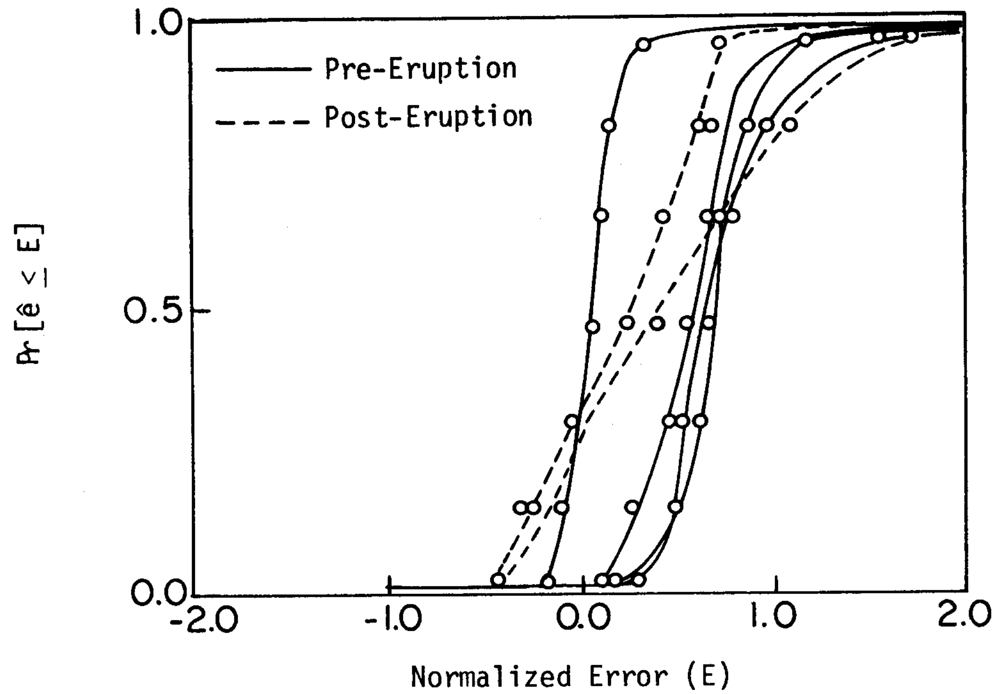

Figure 35. CDFs of Simulation Errors for November (Water Years 1977-1982)

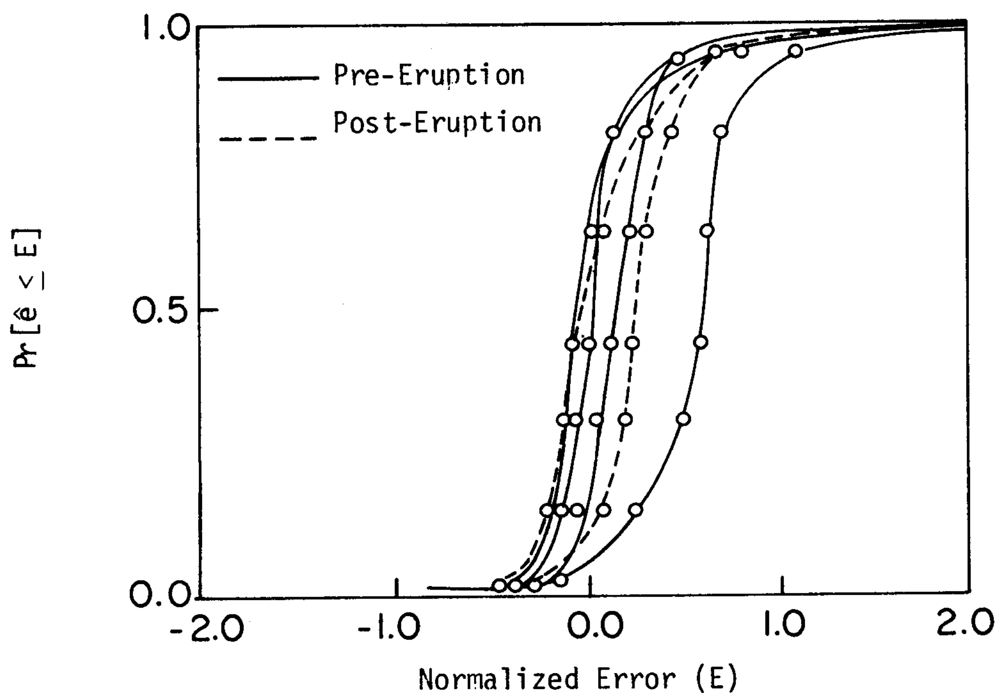

Figure 36. CDFs of Simulation Errors for December (Water Years 1977-1982)

months the error distribution is still spread symmetrically about the zero error line, the changes may not be significant.

For the months June to September, the positive bias in the distribution of $\hat{e}$ becomes more and more prominent. It is clear that for these months the predicted runoff values, based on pre-eruption parameters, are statistically higher than those obtained for the pre-eruption months.

At first this observation may appear counter-intuitive. Initially, it was expected that the infiltration would decrease following the ash deposition. Therefore the predicted values for posteruption conditions should have a negative bias, i.e., predicted - recorded runoff should be less positive, because of a possible increase in runoff due to decreased infiltration. A more careful examination, however, may resolve this apparent paradox.

There are two distinct effects of the eruptions excluding the changes in the channel carrying capacity. One of these changes is caused by the blast and debris deposits along the catchment area which have increased the depression storage capacity and the ponding storage of the catchment, thus reducing the effective portion of gross precipitation available for direct runoff until these depression storages are full. Especially during the months of August and September, these depression storages are dry. Therefore, an increase in the potential storage certainly reduces the runoff compared to pre-eruption conditions. This is evident from the results. During the months of May to July, the significant contribution to streamflow is from the recession flow from subsurface storage. A decrease in the permeability of the soil also reduces the water content in the ground storage available for base flow and the predicted flows are therefore relatively higher compared to the recorded flows for the post-eruption conditions. In the months October to March, when the available depression storages are nearly full and the recession flow is not a significant factor, the slight increase in depression storage and decrease in the infiltration storage may effectively cancel, and the response change is negligible. October of 1980 showed a significant deviation in the precipitation runoff relationship from the pre-eruption conditions. However, this change may be logically concluded to be the immediate consequence of recent eruptions coupled with insufficient rainfall in September 1980.

Summary

The overall conclusion that may be drawn from this investigation is that, for months of high flows the overall response of the catchment to a given gross precipitation remains almost unaffected. However, for the summer months June to September, the post-eruption runoff occurring for a given gross precipitation appears to be lower than that expected from pre-eruption conditions. However, this condition should influence possible increases in flood hazards, especially for the Toutle, where the increases in flood hazards are more related to the changes in travel time and channel carrying capacity due to direct deposits of silt and debris, than to changed runoff response.

These changes were analyzed on a monthly basis and on a daily time scale. Therefore, similar inferences can be drawn for seasonal responses, when the effects applicable to daily events are lumped together to predict changes in seasonal response of the catchment.

CHAPTER VII

SUMMARY AND CONCLUSIONS

Summary

The series of Mt. St. Helens eruptions starting with the primary May 18, 1980 event resulted in significant physical changes in the catchments of Eastern and Western Washington. Some areas of Western Washington in the immediate vicinity of the mountain were affected by direct blast deposits as well as areal ash fallout, while Eastern Washington was affected only by the ashfall. The Toutle River basin was one of the areas most severely impacted by massive mudflows, pyroclastic flows, and debris avalanche deposits. As a result, the channel carrying capacity was severely reduced and the watershed was affected by changes in vegetation cover and alteration of land forms. The ash deposits also reduced the infiltrability and permeability of the soil column.

Therefore, the Toutle River basin was chosen as the site for this investigation. In addition to its proximity to the mountain, the Toutle is unregulated by upstream storage reservoirs, unlike some other rivers in this area. This was an important factor in choosing a river basin. Otherwise any assessment of changes would be severely handicapped by the reliability of the runoff data.

The Toutle River, which drains an area of 474 mi^2 at the USGS gauge near Silver Lake, is characterized by high annual mean precipitation, which varies by a factor of at least two over the basin 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 occur in December or January as a result of heavy precipitation accompanying a warm front, which results in rapid snowmelt.

Areas of Eastern Washington were also affected by heavy ashfall following the Mt. St. Helens eruptions. Existence of diversions and regulations in almost all the streams in the ash-affected regions precluded considering them for this investigation. Crab Creek was chosen as a potential catchment because of absence of such diversions and regulations, and also because of the location of this catchment in the area affected by more than one inch of ash deposition. The efforts to model the precipitation-runoff process, either by the NWS (runoff) model or the modified CLS model were unsuccessful. Therefore, no conclusions could be drawn about the possible changes of hydrologic response in this area. However, such changes are not expected to be very significant due to the extensive agricultural use of the land and the extremely high evaporation demand compared to precipitation.

Modeling of the precipitation-runoff process for the Toutle River started with the estimation of the snowmelt by the NWS snow accumulation and ablation model (Anderson, 1973). Initially, output from this model was used to simulate the runoff by the NWS soil moisture accounting model (Burnash et al., 1973). Later the Constrained Linear System (CLS) model, with some modifications was found more suitable. The modified model preprocesses the gross precipitation input to the original CLS model to compute the effective precipitation. An impulse response function is estimated for converting this effective precipitation to runoff.

This model was calibrated for the period October 1972 to September 1976 for the Toutle River on a daily time scale. The parameters obtained from this calibration were then used in the prediction mode of the model where the runoff was simulated from the gross precipitation, using the parameters calibrated using pre-eruption conditions. This model was run in a prediction mode for the period October 1976 to September 1982, which covers more that two years of post-eruption period. The prediction errors for the entire prediction period were then computed on a daily scale and statistically analyzed on a calendar month basis for all the years of prediction.

Conclusions

An analysis of the statistical properties of the errors showed that:

1) the overall hydrologic response of the catchment remains practically the same for the months October to March; and
2) for other months the post-eruption runoff for given precipitation is less than under pre-eruption conditions.

These results can be explained on the basis of a decrease in the soil permeability and thus the infiltration amount for given precipitation, and an increase in ponding or depression storage capacity due to debris and blast deposits in the catchment.

This investigation was carried out with a relatively short post-eruption record length. Therefore, it should be evident that there is some uncertainty in the conclusions. However, these results seem to be confirmed by intuitive judgments based on other physical information.

The overall effect of the major Mt. St. Helens eruptions is much more complex. The integrated results of the ashfall, and direct blast material deposits have greatly increased the flood hazard in the Toutle River Basin. Sudden failure of the debris dams formed in the basin following the eruptions and an eventual overflow of Spirit Lake and Coldwater Lake would be disastrous. The change of hydrologic response of the catchments due to ashfall effects appears insignificant compared to other changes resulting from direct blast material deposits.

APPENDIX - A GLOSSARY OF TERMS USED IN THE SACRAMENTO (NWS) SOIL MOISTURE ACCOUNTING 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 - 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 may be 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.

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.

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