LONG TERM HYDROLOGIC SIMULATION USING SCS-CN METHOD

A DISSERTATION

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By

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CANDIDATE'S DECLARATION

I hereby certify that the work, which is being presented in this dissertation entitled **"LONG TERM HYDROLOGIC SIMULATION USING SCS-CN METHOD"** in the partial fulfillment of the requirements for the award of the degree of Master of Technology in "WATER RESOURCES DEVELOPMENT (CIVIL)" submitted to the DEPARTMENT OF WATER RESOURCES DEVELOPMENT AND MANAGEMENT, Indian Institute of Technology Roorkee, Roorkee, is an authentic record of my own work carried out during the period from July 2005 to June 2006 under the supervision of Dr. S. K. Mishra, Assistant Professor, Department of Water Resources Development and Management, Indian Institute of Technology Roorkee, Roorkee and Dr. Sanjay Kumar Jain, Scientist E1, National Institute of Hydrology, Roorkee.

I have not submitted the matter embodied in this dissertation for the award of my any other degree.

Date: 19-06-2006

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This is to certify that the above statement made by the candidate is correct to best of our knowledge.

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LIST OF SYMBOLS

AMC 1	AMC corresponding to dry condition;
AMC II	AMC corresponding to normal condition;
AMC III	AMC corresponding to wet condition;
AMC	Antecedent moisture condition;
AVP	average annual rainfall;
AVQ	average annual runoff;
b_c	depletion coefficient;
CN	Curve number;
CN_0	Curve number at time t = 0;
CN_I	curve number corresponding to AMC I;
CN_{II}	curve number corresponding to AMC II;
CNIII	curve number corresponding to AMC III;
CN_t	curve number at time t;
d_0, d_1, d_2	routing coefficients;
DP	average daily depletion;
E	lake evaporation;
E_t	average monthly lake evaporation for day t;
F	actual infiltration;
F^2	index of disagreement;
F_c	cumulative static portion of total infiltration;
F_d	cumulative dynamic portion of total infiltration;
g_0, g_1, g_2	base flow routing coefficients;
I_a	initial abstraction;
K	storage coefficient;
Kb	base flow storage coefficient;
M	soil moisture index at beginning of the first storm;
M_A	average soil moisture index;
M_t	soil moisture index at any time t;
n	number of values (time steps) within the considered time period;

P	total rainfall;
PANC	ratio of the potential maximum retention at a time t to the absolute potential maximum retention;
PET	potential evapotranspiration;
Q	direct surface runoff;
Q_b	base flow;
$QOBS_i$	recorded value at time step I;
$QSIM_i$	simulated value at time step I;
Q_t	total daily flow;
R^2	coefficient of correlation;
S	potential maximum retention;
S_0	potential storage space available in the soil column for water retention;
S_{abs}	absolute potential maximum retention;
T	no. of days between storms
t	time;
λ	initial abstraction coefficient;

ABSTRACT

Estimation of monthly runoff is required for planning and management of the water resources projects. The rainfall in monsoon season mainly contributes to annual runoff. The runoff during non-monsoon season however also depends on the base flow, and it decreases because of the excessive pumping of ground water wells. For estimation of runoff, a number of models varying from the simplest empirical relations to the most complex physically based models are available in literature. The Soil Conservation Service Curve Number (SCS-CN) method is one of the simplest and most popular methods available and widely used world over for predicting direct surface runoff from given storm rainfall amount. Of late, the method has also been employed in long term hydrologic simulation.

In this study, an SCS-CN-based model is proposed and applied to the 9-year daily data of a watershed (area = 2785 sq. km) of Sutlej River. The Sutlej River Catchment from Rampur to Kasol located in Himachal Pradesh is selected for the study. It is a major river of the Indus System, which originates from Mansarovar Lake in Tibet. The total catchment area of Sutlej River from Rampur to Kasol is about 2785 sq. km. The watershed is hilly and has mostly forest and barren land.

The available nine years of data was split into two parts; the first five years data were used for calibration, and the rest four years data for validation. Besides a yearly volumetric analysis, a sensitivity analysis of the four parameters of the proposed model was also carried out. The model performance degraded with the increase in length of data. In yearly simulations as well in calibration and validation, model showed a satisfactory performance. The model simulated the yearly runoff values with significantly low relative errors, further indicating a satisfactory performance. Notably, the yearly runoff volume was not taken as a constraint in parameter optimization and it further supports the model validity and dependability. The least sensitive and most significant parameter S_0 of the SCS-CN model indicated its amenability to field applications employing the NEH-4 CN values or the CN values derived using remote sensing data. Over and above all, the model is simple, has four parameters, and dependable.

CHAPTER 1

INTRODUCTION

1.1 GENERAL

The problem of transformation of rainfall into runoff has been subject of scientific investigations throughout the evolution of the subject of hydrology. Hydrologists are mainly concerned with evaluation of catchment response for planning, development and operation of various water resources schemes. A number of investigators have tried to relate runoff with different watershed characteristics affecting it. For simulation of the rainfall-runoff process and design flood evaluation, conceptual and physically based models are widely used. Long–term hydrologic simulation is required for augmentation of hydrologic data; to delineate vulnerable areas of the watershed contributing to sediment yield, which is significantly related with the direct surface runoff generated by the watershed; for analysis of water availability; computation of daily, fortnightly, and monthly flows for reservoir operation; and drought analyses. Since the rainfall data are generally available for a much longer period than are the stream flow data, long – term hydrologic simulation helps extend the gauged data required for the above applications. Thus, it is useful for water resources planning and watershed management.

Stream flow representing the runoff phase of the hydrologic cycle is the most important basic data for hydrologic studies. The first and foremost requisite for the planning of water resources development is accurate data of stream flow, or in other words, the surface runoff for a considerable period of time to determine the extent and pattern of the available supply of water. The usual practical objective of a hydrologic analysis is to determine the characteristics of the hydrograph that may be expected for a stream draining any particular watershed. Surface runoff is that portion of the precipitation, which, during and immediately following a storm event, ultimately appears as flowing water in the drainage network of a watershed. Such flow may result from direct movement of water over the ground surface, precipitation in excess of abstraction demands, or it may result from emergence of soil water into drainage ways.

In addition to unit hydrograph based approach, hydrological modelling is another approach for runoff estimation. The key outcomes of hydrologic models (*rainfall-runoff models*) are flow hydrographs. Simulating the transformation of rainfall into runoff at the catchment scale using mathematical models has seen considerable developments since the early 1960s due to increasing computing capacities. Now there exists a large number of models in literature, among which are the spatially lumped conceptual or empirical types that represent the link between rainfall and stream flow by a series of interconnected storage elements. The available popular rainfall-runoff models are HEC-HMS, SHE, MIKE-11, SWMM etc. These models are useful for the hydrologic and hydraulic engineering planning and design as well as water resources management.

The available models can be categorised into lumped, distributed, and physically based models. The basic unit of a lumped model is normally taken to be a sub basin of the total watershed being considered. In this type of model, empirical approaches are also applied. In comparison, physics based models employ some or the other form of water balance equation defined at all points to model runoff flows. The most common approach is the application of the Saint Venant equations of shallow water flow or its variant, which conserve water momentum. There are some models, which do not fit conveniently in classification of lumped or physics based models.

A hydrologic model can be defined as a mathematical representation of the flow of water and its constituents on some part of the land surface or subsurface environment. Hydrologists are mainly concerned with evaluation of catchment response for planning, development and operation of various water resources schemes. Computer models began to appear in the mid 1960s, first for surface water flow and sediment transport, then in the 1970s for surface water quality and ground water flow, then in 1980s for ground water transport. Conventional models require considerable hydrological, meteorological and spatial data.

Rainfall-runoff methods developed during the early 1940's utilized infiltration data for computing the runoff amount. Andrews (1954) eventually developed a graphical rainfall runoff method taking into account the soil texture, type and amount of cover and conservation practices, combined into what is referred as soil cover complex or soil-vegetation- land use (SLV) complex (Miller and Cronshey, 1989). According to Rallison and Miller (1982), the method given by Mockus (1949) and Andrews (1954) were transformed and generalized to yield the existing SCS-CN method so that it could generally be used universally and was also applicable to ungauged watersheds.

1.2 OBJECTIVE OF THE STUDY

The primary objective of the study is to propose a simple Soil Conservation Service Conservation Curve Number (SCS-CN) Method based long daily flow simulation model and test for its workability using the data of a watershed of Sutlej river basin.

1.3 SCOPE OF THE STUDY

The study is organized as follows:

Chapter 2 provides a brief review of literature available on the available rainfall-runoff simulation methods, historical background, and other details relevant to the study.

Chapter 3 contains the theory of SCS-CN method, which has been used in model development in the present study.

Chapter 4 describes the proposed methodology of the study as well as, in detail the model calibration and validation.

Chapter 5 provides features of the Sutlej river catchment in Himachal Pradesh (India), the data of which have been used for model testing.

Chapter 6 provides a discussion of the results of model calibration and validation and its general performance on the field data.

Chapter 7 summarizes and concludes the study.

The developed computer program is incorporated at the end of dissertation work (Appendix -I).

CHAPTER 2

REVIEW OF LITERATURE

The origin of rainfall-runoff modeling, widely used for flow simulation, can be found in the second half of the 19th century when engineers faced the problems of urban drainage and river training networks. During the last part of 19th century and early part of 20th century, the empirical formulae were in wide use (Dooge, 1957, 1973). The approaches were mainly confined to small and mountainous watersheds. Later attempts were mainly confined to extend their application to larger catchments. In 1930's, the popular unit hydrograph and instantaneous unit hydrograph techniques were developed. With the advent of computers in 1950's, sophistication to models through mathematical jugglery was introduced with the objective of proving the generality of available approaches. The subsequent era saw the development of a number of models and evoked the problem of classification (Dooge, 1973; Todini, 1988).

2.1 CLASSIFICATION OF HYDROLOGICAL MODELS

The available hydrological models can be broadly classified into deterministic Models, lumped conceptual models, and fully distributed, physically-based models, a brief description of which is provided as below.

2.1.1. Deterministic Models

Deterministic models can be classified according to whether the model utilizes a spatially lumped or distributed description of the catchment area, and whether the description of the hydrological processes is empirical, conceptual or fully physically-based. In practice, most conceptual models are also lumped and most fully physically based models are also distributed.

2.1.2. Lumped conceptual models

These occupy an intermediate position between the fully physically based approach and empirical black-box analysis. Such models are formulated on the basis of a relatively small number of components, each of which is a simplified representation of one process element in the system being modeled.

2.1.3. Fully Distributed, Physically-Based Models

These are based on our understanding of the physics of the hydrological processes, which control catchment response and use physically based equations to describe these processes. From their physical basis such models can simulate the complete runoff regime, providing multiple outputs (e.g. river discharge, phreatic surface level and evaporation loss) while black box models can offer only one output. Also, almost by definition, physically based models are spatially distributed since the equations from which they are formed generally involve one or more space coordinates. They can therefore simulate the spatial variation in hydrological conditions within a catchment as well as simple outflows and bulk storage volumes. On the other hand, such models require large computational time and data and are costly to develop and operate.

In this study, a simple, lumped, conceptual, and empirical Soil Conservation Service Curve Number (SCS-CN) method, a detailed description of which is provided in the forthcoming chapter, was used for long term hydrologic simulation, a brief review of such studies is in order.

2.2 LONG TERM HYDROLOGIC SIMULATION

Long –term hydrologic simulation is required for augmentation of hydrologic data. It is useful for water resources planning and watershed management. Long- term hydrologic data are specifically required for analysis of water availability; computation of daily, fortnightly, and monthly flows for reservoir operation; and drought analyses. Since the rainfall data are generally available for a much longer period than are the stream flow data, long – term hydrologic simulation helps extend the gauged data required for the above applications.

There exists a multitude of models for hydrologic simulation. In 1991, the U. S. Bureau of Reclamation prepared an inventory of 64 watershed models into four categories and the inventory is being updated. Burton (1993) compiled Proceedings of the Federal Interagency Workshop on Hydrologic Modeling Demands for the 1990's, which contains several important watershed hydrology models. Singh (1995) edited a book that summarized 26 popular models from around the globe. The subcommittee on hydrology of the Interagency Advisory Committee on Water Data (1998) published proceedings of the

First Federal Interagency Hydrologic Modeling Conference, which contains many popular watershed hydrology models developed by federal agencies in the United States. Wurbs (1998) listed a number of generalized water resources simulation models in seven categories and discussed their dissemination.

The available models vary in description of the components of the hydrologic cycle, degree of complexity of inputs, number of parameters to be determined, time interval used, and output generated. Some models like Hydrologic Simulation Package Fortran (HSPF), USDAHL (Holtan and Lopez, 1971) and its variants, System Hydrologic Europeen (SHE), Hydrologic Engineering Center (HEC), Hydrologic Modeling System (HMS) (HEC,2000), etc. have a number of parameters, usually use a short time interval, and produce hydrographs as well as water yield. The HSPF and SHE models are not applicable to ungauged watersheds for the reason that their application requires priori calibration with measured runoff data for each watershed. The USDAHL model can, however, be used for ungauged watersheds, but the prediction accuracy is not commensurate with the input detail. These models are better suited for detailed scientific, hydrologic studies. Holtan and Lopez (1971) found the USDAHL MODEL to explain about 90% of the variation in monthly runoff for four watersheds up to 40 sq. km. The Haan (1975) model has four parameters, uses a 1-d time interval (except for a 1-hr interval is used during rains), has simple inputs, and only outputs runoff volume. In testing, this model was reported to explain about 80% of the variation in monthly runoff from 46 watersheds of generally less than 100 sq. km. However, no provision exists for estimating the parameters of this model for its employment to ungauged watersheds. Woodward and gburek (1992) compared some of the available models and found them widely varying in their degree of success.

Despite their comprehensive structure, many of these models have not yet become standard tools in hydrologic practice in developing countries, such as India, Pakistan, Nepal, and other countries of Asia as well as African countries. The reason is twofold. First, most basins in these countries of Asia are ungauged and there is a little hydrologic data available. Second, these models contain too many parameters which are difficult to estimate in practice and which vary from basin to basin. Although some of these models have been applied to ungauged basins, the fact is that they are not easy for practical applications. Furthermore, when these models are compared on the same basin, they are found widely varying in their performance (Woodward and Gburek, 1992). Thus, what is needed in developing countries is simple models which can provide reasonable simulations and need little data. The SCS- CN based simulation models to satisfy these criteria.

The SCS-CN method is an infiltration loss model and, therefore, its applicability is supposedly restricted to modeling storms (Ponce and Hawkins, 1996). Notably, the SCS-CN method is theoretically applicable to any watershed of any size as long as the measured runoff corresponds to the observed rainfall amount (Mishra and Singh, 2003). However, some restrictions regarding its application to watershed of less than 250 sq. km. for practical reasons have been reported in literature (for example, Ponce and Hawkins (1996)). Using theoretical arguments, it is possible to apply the SCS-CN method for long-term hydrologic simulation to any basin. It is for this reason that the SCS-CN method computes the rainfall-excess that equals the direct surface runoff. In large watersheds, routing plays an important role in converting the rainfall-excess to surface runoff hydrograph produced at the outlet of the basin. On the other hand, small watersheds require minimal routing in long- term hydrologic simulation utilizing a time interval of 1-d or larger. Consequently, the SCS-CN method has been used in long-term hydrologic simulation and several models have been developed in the past two decades. The models of Williams and LaSeur (1976), Huber et al. (1976) and Knisel (1980) that have been applied with varying degrees of success (Woodward and Gburek, 1992) are notable among others. The model of Soni and Mishra (1985) is a variant of the Hawkins (1978) model. The generally available and frequently cited models of Williams and LaSeur (1976) and Hawkins (1978) along with the recent models of Pandit and Gopalakrishnan (1996) and Mishra et al. (1998) are described to help better understand the mathematical treatment of hydrological processes by the SCS-CN method.

2.2.1 Williams-LaSeur Model

Williams LaSeur (1976) proposed a model based on the existing SCS-CN method which is based on the water balance equation and two fundamental hypotheses (Chapter 3). The SCS-CN parameter potential maximum retention S is linked with the soil moisture (M) according to equation (2.1) expressed as:

$$M = S_{abs} - S \tag{2.1}$$

where, S_{abs} is the maximum potential maximum retention, which is taken as equal to 20 inches. M is depleted continuously between storms by evapotranspiration and deep storage. Depletion is high when soil moisture and Lake Evaporation is high, and most rapid immediately after a storm (high M). M is assumed to vary with the lake evaporation as:

$$\frac{d(M)}{dt} = -b_c M^2 E \tag{2.2}$$

where, t is the time, b_c is the depletion coefficient, and E is the lake evaporation. Equation (2.2) represents a second- order process. The lake evaporation is used as a climatic index. According to Williams and LaSeur, equation (2.2) works well for the average monthly values for runoff predictions. They found their model to perform poorly when used daily pan evaporation and temperature as climatic indices. From equation (2.2) M is solved as:

$$M_t = \frac{M}{1.0 + b_c M \sum_{t=1}^{T} E_t} \tag{2.3}$$

where, M is the soil moisture index at the beginning of the first storm, M_t is the soil moisture index at any time t, E_t is the average monthly lake evaporation for day t, and T is the number of days between storms.

For model operation, the amount of water infiltrated during a rainstorm (= rainfall P – direct surface runoff Q) is added to the soil moisture. The rainfall of the first day of the T-day period is added to M before equation (2.3) is solved. However, runoff is not abstracted from rainfall until the end of the end of the T- day period, for the reason that runoff lags rainfall and may be subjected to depletion for several days on large watersheds. Thus, equation (2.2) is modified for rainfall P as

$$M_t = \frac{M + P}{1.0 + b_c M \sum_{t=1}^{T} E_t} - Q \tag{2.4}$$

Where, P and Q are, respectively, the rainfall and runoff for the first storm. The retention parameter S is computed from equation $S = S_{abs} - M$ for $S_{abs} = 20$ inches for computing runoff for the second storm using the popular form of the existing SCS-CN method, expressible as:

$$Q = \frac{(P - 0.2S)^2}{P + 0.8S} \tag{2.5}$$

The procedure is repeated for each storm in the rainfall series. Thus, the William-Laseur model can also be applied to the pre-identified rainstorms other than 1 day. The model is calibrated with data from a gauged watershed by adjusting the depletion coefficient, b_c, until the predicted average annual runoff matches closely with the measured average annual runoff. The initial estimate of b_c is derived from the average annual rainfall and runoff values as

$$DP = \frac{AVP - AVQ}{365} \tag{2.6}$$

where, DP is the average daily depletion, AVP is the average annual rainfall, and AVQ is the average annual runoff. The value of b_c can be computed from equation (2.4) assuming that (a) T=1 day; (b) M is the average soil moisture index, M_A; (c) E is the average lake evaporation; and (d) P=Q=0 for the day. For this situation, equation (2.4) can be recast as

$$M_t = \frac{M_A}{1.0 + b_c M_A E_t} \tag{2.7}$$

In which, M_A is computed from equations $S = \frac{1000}{CN} - 10$ and $S = S_{abs} - M$ for CN corresponding to AMC II. The average daily depletion computed from equation (2.6) is set equal to the change in soil moisture for 1 day as

$$DP = M_A - M_t \tag{2.8}$$

Combining equation (2.7) and (2.8), one obtains

$$DP = M_A - \frac{M_A}{1.0 + b_c M_A E_t} \tag{2.9}$$

From which b_c can be derived as

$$b_c = \frac{-DP}{E_t M_A (DP - M_A)} \tag{2.10}$$

The simulation begins 1 year before the actual calibration period because of a priori determination of the initial soil moisture index. At the end of one year, the soil moisture is taken to represent the actual soil moisture conditions. Here, the initial estimate of M is M_A.

In brief, the Williams-LaSeur model has one parameter, uses a 1- day or any other pre-determined time interval, has simple inputs and only outputs the runoff volume. It eliminates, to certain extent, sudden jumps in the CN values when changing from one AMC to the other. Its operation requires (i) an estimate of the AMC- II curve number, (ii) measured monthly runoff, (iii) daily rainfall and (iv) average monthly lake evaporation. The model- computed b_c forces an agreement between the measured and the predicted average annual runoff. The model can be applied advantageously to nearby ungauged watersheds by adjusting the curve number for the ungauged watershed in proportion to ratio of the AMC-II curve number to the average predicted curve number for the calibrated watershed.

The model, however, has its limitations. It utilizes an arbitrarily assigned value of 20 inches for S_{abs} and simulates runoff on monthly and annual bases although runoff is computed daily, treating rainfall of a day as a storm. Several adjustments of b_c lose the physical soundness of the model apart from the undesirable loss of 1-year rainfall-runoff information (Singh *et al.,* 2001). Owing to physically unrealizable decay of soil moisture with Lake Evaporation, the model contradicts the SCS-CN approach, as shown below.

Taking $S_{abs} = S_o = S$, which represents S at the beginning of a storm under fully dry conditions. Equation $M = S_{abs} - S$ can be written for time t as: $M_t = S_o - S_t$, if $S_t = 0$ at time $t = 0$, $M_t = S_O$. its substitution into equation (2.3) leads to

$$(S_o - S_t)/S_o = \frac{1}{(1 + b_c S_o \overline{E} t)}, \tag{2.11}$$

where $\overline{E}$ is the average rate of evapotranspiration. Here, $(S_o - S_t)/S_O = F/S_o$, consistent with the description of Mishra (1998) and Mishra and Singh (2002a, b). With the assumption that $P/S_o = b_c S_o \overline{E} t$ and $I_a = 0$ (here, $P/t =$ uniform rainfall intensity $i_o = b_c S_o^2 \overline{E}$), a substitution of these relationships into equation $P = I_a + F + Q$ yields $Q = PS_o/(S_o + P)$ or $Q = PS/(S + P)$, which holds for F in the existing SCS-CN approach, rather than Q, and therefore equation (2.3) is physically unrealizable.

2.2.2 Hawkins Model

Hawkins (1978) derived a daily simulation model by expressing equation (2.5) as;

$$Q = P - S\left(1.2 - \frac{S}{P + 0.8S}\right) \qquad (2.12)$$

which is valid for $P \geq 0.2S$. It is evident from this equation that as $P \rightarrow \infty$, the maximum possible water is equal to S_t and it is computed as

$$S_t = 1.2S \qquad (2.13)$$

which can be derived from equation $S_T = (1 + \lambda)S$

assuming $\lambda = 0.2$.

Substitution of equation $S = \frac{1000}{CN} - 10$ for S into equation (2.13) yields a storage relation for any time t as

$$S_{T(t)} = 1.2S_t = 1.2\left(\frac{1000}{CN_t} - 10\right) \qquad (2.14)$$

where subscript 't' represents the time level. Taking into account the evapotranspiration (ET) ,the maximum water loss at a higher time level ($t + \Delta t$), where Δt is the storm duration, can be derived from the moisture balance as:

$$S_{T(t+\Delta t)} = S_{T(t)} + \left[ET - (P - Q)_{(t,t+\Delta t)}\right] \qquad (2.15)$$

Where the last term in the bracket corresponds to the Δt duration between time t and ($t + \Delta t$), denoted by subscript (t, t+Δt). Following the above argument, equation (2.15) can be alternatively be written as

$$S_{T(t+\Delta t)} = 1.2S_{(t+\Delta t)} \qquad (2.16)$$

Here it is noted that ET also intuitively accounts for the interim drainage, if any. Coupling of equation (2.15) with equation (2.16) and substitution of equation $S = \frac{1000}{CN} - 10$ into the resulting expression leads to

$$1.2\left(\frac{1000}{CN_t} - 10\right) + \left[ET - (P - Q)\right]_{(t,t+\Delta t)} = 1.2\left(\frac{1000}{CN_{t+\Delta t}} - 10\right) \qquad (2.17)$$

which can be solved for $CN_{t+\Delta t}$ as:

$$CN_{t+\Delta t} = \frac{1200}{\frac{1200}{CN_t} + [ET - (P - Q)]_{(t, t+\Delta t)}} \tag{2.18}$$

Since ET, P and Q in the equation (2.18) correspond to the time duration Δt and these are known quantities, Q can be computed from equation (1) for a given CN_t. Input of these values along with the known value of ET yields CN at time level ($t + \Delta t$).

It is apparent from the above that the Hawkins model accounts for the site moisture on a continuous basis using the volumetric concept. It is worth emphasizing here that the Hawkins model is analogous to a bottomless reservoir, implying that the reservoir never depletes fully or the reservoir is of infinite storage capacity. Such a description is, however, physically realizable in terms of $\psi - \theta$ relationship, according to which S is directly proportional to the average ψ which approaches infinity as $\theta \to 0$. Under the situation that the soil is fully saturated or $\theta \to n$ (soil porosity), $\psi \to 0$. Thus similar to S, S_T will also vary from 0 to ∞ . Following this argument, S_{abs}= 20 inches in the Williams- LaSeur model appears to be a forced assumption. While applying the Hawkins model, Soni and Mishra (1985) also employed a similar assumption by fixing the depth soil profile to the root zone of 1.2m for computing S.

The advantage of Hawkins model is that it also eliminates sudden quantum jumps in the CN values when changing from one AMC level to the other, similar to the William-LaSeur model. However, the Hawkins model also has the following limitations.

1. It does not distinguish the dynamic infiltration from the static one. The water drained down to meet the water table may not be available for evapotranspiration.
2. The interim drainage is coupled with the evapotranspiration intuitively.
3. According to the model formulation, equation (2.12), the term ($I_a + S$) takes part in the dynamic infiltration process, rather than the S alone. As the initially adsorbed water ($= I_a$) as a result of very high capillary suction is not available for transpiration, I_a does not play a part in the dynamic infiltration process.

4. The follow up of the above 3.leads to the assumption of the SCS-CN method to be based on the $(I_a + S)$ scheme, whereas I_a is separate from S. It is noted that the Hawkins model considers the maximum F amount equal to $(I_a + S)$.
5. Substitution of P = 0 in equation (2.12) yields Q = 0.05 S, which is impossible. Although equation $P = I_a + F + Q$

$P \rightarrow$ Total rainfall

$I_a \rightarrow$ Initial abstraction

$F \rightarrow$ Actual infiltration

$Q \rightarrow$ Direct surface runoff

is stated to be valid for $P \geq 0.2S$, equation (2.12) carries its impacts by allowing an additional storage space of 20% of S available for water retention at every time level and, in turn, leads to unrealistic negative infiltration at $P \rightarrow 0$. Thus, at time t $(= S_t)$ corresponds to CN at time $t(= CN_t)$. Equation (2.12), therefore needs modification by substitution of 1000 for 1200.

2.2.3 Pandit and Gopalakrishnan Model

Pandit and Gopalakrishanan (1996) suggested a continuous simulation for computing the annual amount of runoff for computing annual pollutant loads. This model is specifically useful for urban areas characterized primarily by the percent imperviousness. It involves the following steps:

(i) Determine the pervious curve number for AMC II.

(ii) Determine the directly connected impervious area of the urban watershed.

(iii) Estimate daily runoff depth for both pervious and impervious areas separately using equation (2.5).

(iv) Determine the actual AMC based on the pervious 5- day rainfall and modify CN using equations

$$CN_I = \frac{CN_{II}}{2.281 - 0.01281 CN_{II}};\ r^2 = 0.996 \text{ and SE=1.0CN} \qquad (2.19a)$$

$$CN_{III} = \frac{CN_{II}}{0.427 + 0.00573 CN_{II}};\ r^2 = 0.994 \text{ and SE= 0.7 CN} \qquad (2.19b)$$

Such that CN does not exceed 98.

NEH-4 identified three antecedent moisture conditions (AMC): AMC I, AMC II, and AMC III for dry, normal and wet conditions of the watershed, respectively. As shown in Fig. 2.1, AMC I corresponds to the lower enveloping CN, AMC II the median CN, and AMC III the upper enveloping CN. NEH-4 provides conversion table from CN for AMC II to corresponding CNs for AMC I and AMC III.

(v) Calculate the yearly storm runoff depth by assuming the runoff for each day.

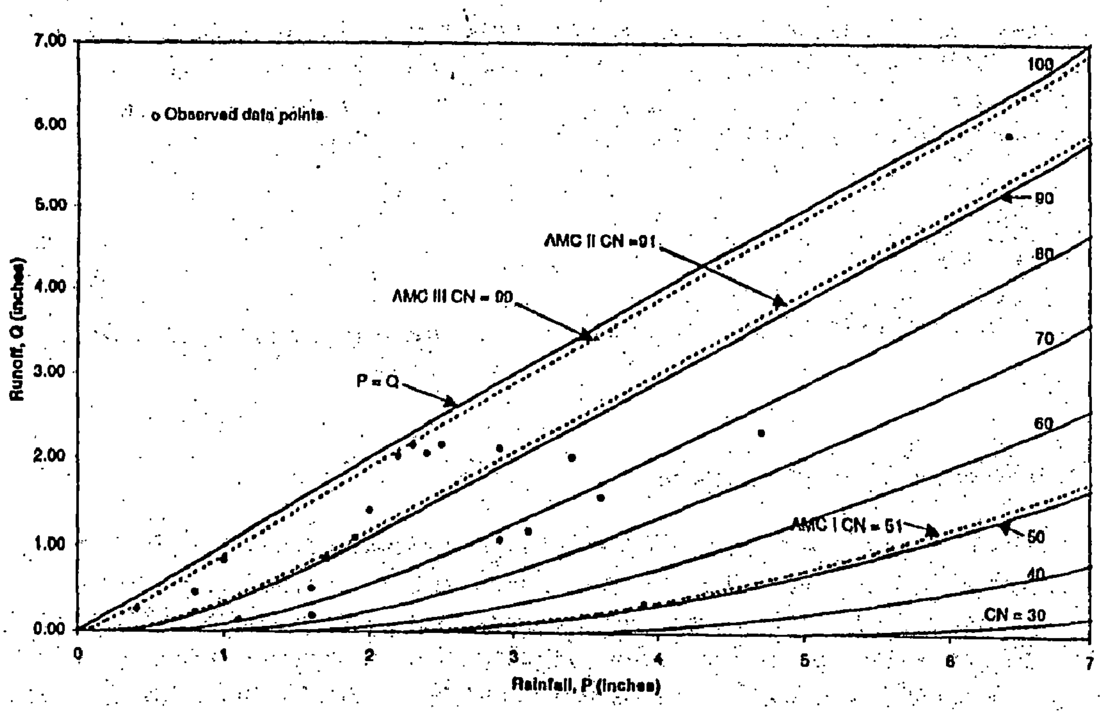

Figure 2.1: Determination of CN for AMC I through AMC III using existing SCS-CN model

In summary, the method is very simple, allows sudden jumps in CN values, and ignores evapotranspiration, drainage contribution, and watershed routing. Since routing is ignored, it is useful for small watersheds, where routing is minimal in daily runoff computation. This model is a specific form of the Mishra et al. (1998) model described subsequently.

2.2.4 Mishra et al. model

The Mishra et al. model assumes CN variation with time dependent on AMC (Ponce and Hawkins, 1996) only. The computed rainfall- excess Q(equation2.5) is transformed to direct runoff DO_t using a linear regression approach, analogous to the unit hydrograph scheme. Taking baseflow (O_b) as a fraction of F along with the time lag, the total daily flow, Q_t, is computed as the sum of DO_t and O_b. the model parameters are optimized utilizing as objective function of minimizing the errors between the computed and observed data.

The advantage of the Mishra et al. (1998) model is that it allows the transformation of rainfall- excess to direct runoff and takes into account the baseflow, enabling its application to even large basins. The model, however, has the following limitations.

(1) It does not distinguish between dynamic and static infiltration, similar to the Williams-LaSeur Hawkins models.

(2) It allows sudden jumps in CN values when changing from one AMC to another AMC level.

(3) The use of linear regression equation invokes the problem of mass balance, for the sum of regression coefficients is seldom equal to 1.0 in long-term hydrological simulation.

(4) The baseflow is taken as a fraction of F, which is not rational. The water retained in the soil pores may not be available for baseflow, rather the water that percolates down to the water table may appear at the outlet as baseflow. Thus, there exists a need for an improved model that eliminates for the most part these limitations, leading to the formulation of a model based on the modified SCS-CN method (Mishra and Singh, 2002a; Mishra et al., 2003).

CHAPTER 3

SCS-CN METHODOLOGY

The Soil Conservation Service-Curve Number (SCS-CN) method is one of the most popular and simple methods used in rainfall-runoff modeling. Its simplicity lies in the fact that it requires less number of inputs, such as rainfall data and a single parameter called as Curve Number (CN) to estimate the runoff. The SCS-CN method was developed in 1954 and is documented in Section 4 of the National Engineering Handbook (NEH-4) published by the Soil Conservation Service (now called the Natural Resources Conservation Service), U.S. Department of Agriculture in 1956. The document has since been revised in 1964, 1965, 1971, 1972, 1985, and 1993. The SCS-CN method is the result of exhaustive field investigations carried out during the late 1930s and early 1940s and the works of several early investigators, including Mockus (1949), Sherman (1949), Andrews (1954), and Ogrosky (1956). The passage of Watershed Protection and Flood Prevention Act (Public Law 83-566) in August 1954 led to the recognition of the method at the Federal level and the method has since witnessed myriad applications all over the world. It is one of the most popular methods for computing the volume of surface runoff for a given rainfall event from small agricultural, forest, and urban watersheds. The method is simple, easy to understand and apply, stable, and useful for ungauged watersheds. The primary reason for its wide applicability and acceptability lies in the fact that it accounts for most runoff producing watershed characteristics: soil type, land use/treatment, surface condition, and antecedent moisture condition. This chapter describes the existing SCS-CN method, the concept of curve number and factors affecting it, and its advantages and limitations.

In mid 1930's, an acute need for hydrologic data for design of conservation practices was felt and eventually, the Soil Conservation Service (SCS) was established under the United States Department of Agriculture (USDA). The major objectives of SCS were to set up demonstration conservation projects and evaluate the design and construction of soil and water conservation practices. To that end, several experimental watersheds were set up at different locations for collecting data on rainfall, runoff, and associated factors. According to the Flood Control Act of 1936 (Public Law 74-738), USDA carried out surveys and investigations for installing measures for retarding flows from watersheds, which is a classical hydrologic problem. It eventually led to the evaluation of the effect of watershed treatment and/or conservation measures on the rainfall-runoff process. The data collected from experimental watersheds were, however, found to be scant and covering only a marginal fraction of the conditions affecting the rainfall-runoff process in watersheds (Andrews, 1954). Therefore, a need for collecting data for carrying out infiltration studies was felt.

Using the sprinkler-type infiltrometer, thousands of infiltration tests on field plots of 6 feet wide and multiples of 12 feet long were carried out during the late 1930's and early 1940's. For economic reasons, another FA infiltrometer (Rallison and Miller, 1982) was devised for plots of 12 x 30 inches and it was used extensively. Using these infiltration data, a rational method for estimating runoff under various cover conditions was developed. For that purpose, SCS hired three private consultants, W. W. Horner, R. E. Horton, and R. K. Sherman. Horton (1933) characterized the infiltration capacity curves and Horner (1940) concentrated on the development of infiltration capacity from small watershed data. Their studies resulted in the development of a series of rainfall retention rate curves and rainfall-excess and time-of-excess curves for computing runoff volume from field plots. This method, however, required time-distributed rainfall data, and therefore, its application was severely restricted in many areas.

3.1 SCS-CN Theory

The SCS-CN method consists of

(a) Water balance equation:

$$P = I_a + F + Q \tag{3.1}$$

(b) Proportional equality hypothesis:

$$\frac{Q}{P - I_a} = \frac{F}{S} \tag{3.2}$$

(c) I_a-S hypothesis

$$I_a = \lambda S \tag{3.3}$$

Where, P= total rainfall, I_a=initial abstraction, F=cumulative infiltration excluding I_a, Q= direct runoff, and S= potential maximum retention or infiltration, also described as the potential postinitial abstraction retention (McCuen, 2002). All quantities in above equation (A) through (C) are in depth or volumetric units.

The fundamental hypothesis equation (B) is primarily a proportionality concept as shown in Fig.3.1.

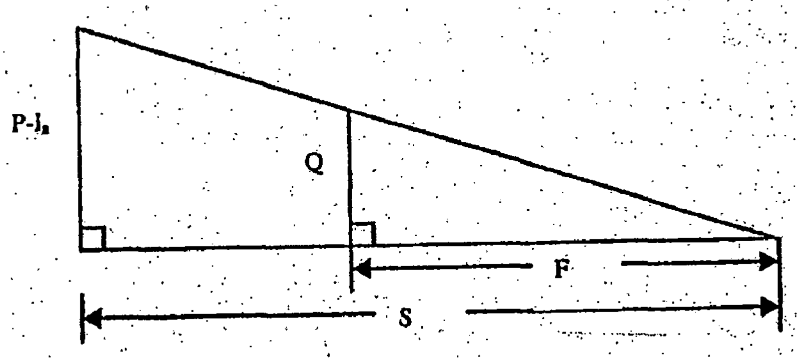

Figure 3.1: Proportionality concept

Apparently, as $Q \rightarrow (P-I_a), F \rightarrow S$. This proportionality enables partitioning (or dividing) ($P-I_a$) into two surface water (Q) and subsurface water (F) for given watershed characteristics or S. This partitioning, however, undermines the saturated overland flow or source area concept that allows runoff generation from only saturated or wet portions of the watershed. Consequently, the statistical theory (Moore and Clarke, 1981; 1982; 1983; Moore, 1983; 1985) based on the runoff production from only saturated (independent or interacting) storage element is negated. According to the SCS-CN method, the extent of runoff contribution of a storage element depends on its capacity or, alternatively, the magnitude of S and, therefore, the whole watershed should contribute to runoff, if S is taken to be a definite quantity. Thus the ratio of the wet and total areas describing the contributing portion should be equal to one.

Parameter S of the SCS-CN method depends on the soil type, land use, hydrologic condition, and antecedent moisture condition (AMC). The initial abstraction accounts for the short- term losses, such as interception, surface storage, and infiltration. Parameter λ is frequently viewed as a regional parameter dependent on geologic and climatic factors (Bosznay, 1989; Ramasastri and Seth, 1985). The existing SCS-CN method assumes λ to be equal to 0.2 for practical applications. Many other studies carried out in the United States and other countries (SCD, 1972; Springer et al., 1980; Cazierand Hawkins, 1984; Ramasastri and Seth, 1985; Bosznay, 1989) report λ to vary in the range of (0,0.3)

The second hypothesis of the SCS-CN method ($I_a = \lambda S$) linearly relates the initial abstraction to the maximum potential retention. It is based on the results of Figure 3.2 (SCS, 1971) depicting the plot between I_a and S. The data for S and I_a were derived from rainfall- runoff records of watersheds less than 10 acres in area.

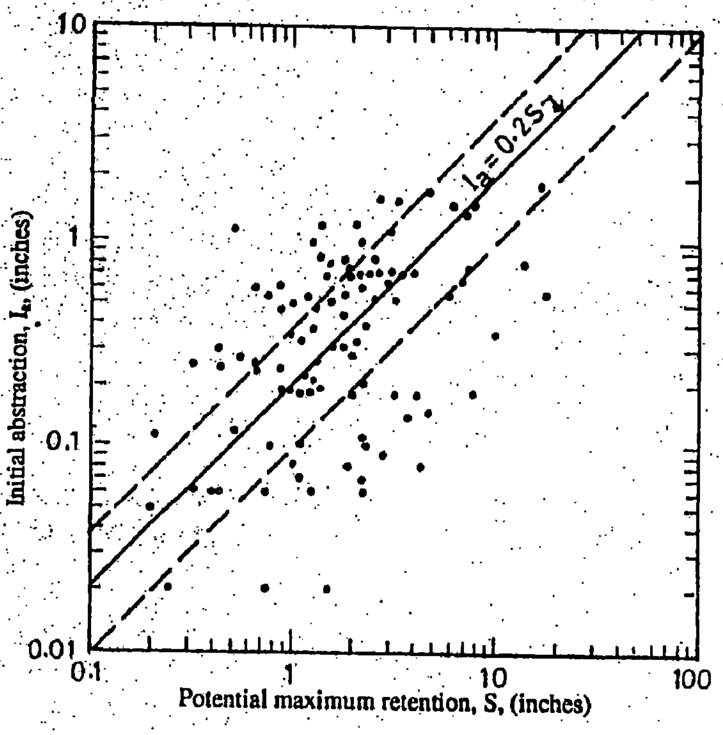

Figure 3.2: Relation between initial abstraction Ia and potential maximum retention, S.

The S values were derived from rainfall- runoff plots prepared for determining CN for AMC II. It is apparent from Fig.3.2 that more than 50% the data points lie within the limits of $0.095 \leq \lambda \leq 0.038$. Errors in S were largely attributed to the computation of the average rainfall of the watershed. The I_a- values were computed by accumulating the rainfall amount from the beginning to the time of start of runoff. The large scatter in the data points in Fig. 3.2 was attributed to the errors in the estimates of I_a due to (SCS, 1971):

(i) The difficulty in determining the actual time of the start of rainfall because of storm travel and lack of instrumentation

(ii) The difficulty in determining the time of the start of runoff largely due to time lag in runoff from the watershed, and

(iii) Impossible determination of the amount of interception losses prior to runoff and its delayed contribution to runoff. As originally hypothesized (SCS,1971),parameters includes I_a.For this condition, equation $I_a = \lambda S$ can be re-written as (Chen,1982):

$$I_a = \frac{\lambda}{1-\lambda} S \qquad (3.4)$$

For $\lambda = 0.2$ equation (3.4) is recast as I_a=0.25S. Combining equation (3.1) and (3.2), the popular form of the SCS-CN method is obtained:

$$Q = \frac{(P - I_a)^2}{P - I_a + S} \qquad (3.5)$$

This equation is valid for $P \geq I_a; Q = 0$ otherwise. For $\lambda = 0.2$, equation (3.5) can be written as

$$Q = \frac{(P - 0.2S)^2}{P + 0.8S} \qquad (3.6)$$

Where Q = actual amount of direct surface runoff

P = total rainfall (or maximum potential surface runoff)

I_a = Initial abstraction

S = potential maximum retention

The existing SCS-CN method equation (3.6) is a one parameter model for computing surface runoff from daily storm rainfall, for the method was originally developed using daily rainfall-runoff data of annual extreme flows (Rallison and cronshey, 1979). Mockus (1964) [In: Rallison, 1980] described the physical significance of parameter S of equation (1) as follows: "...S is that constant and is the maximum difference of (P-Q) that can occur for the given storm and watershed conditions. S is limited by either the rate of infiltration at the soil surface or the amount of water storage available in the soil profile, whichever gives the smaller S value. Since infiltration rates at the soil surface are strongly affected by the rainfall impact, they are strongly affected by the rainfall intensity." This description, however, compares the magnitude of infiltration rate with the volume of water retention in the soil, which is unwarranted.

Since parameter S (mm) in equation (3.6) can vary in the range of $0 \leq S \leq \infty$, it is mapped into a dimensionless curve number (CN), varying in a more appealing range $0 \leq CN \leq 100$, as follows:

$$S = \frac{25400}{CN} - 254 \tag{3.7}$$

The underlying difference between S and CN is that the former is a dimensional quantity (L) whereas the latter is a non-dimensional quantity. Although CN theoretically varies from 0 to 100, the practical design values validated by experience lie in the range (40, 98) (Van Mullem, 1989).

Since its inception, the method has been modified, restructured, strengthened based on its limitations and applications. In fact, it is renamed too as "Natural Resources Conservation Service – Curve Number (NRCS-CN) method" from 1994 onwards, primarily with objective to widen the scope. The only unknown parameter of this method is the CN, which is estimated in various ways by researchers. CN is varied as CN_{I}, CN_{II} or CN_{III} according to the antecedent 5-d rainfall index. Each storm is assigned a CN-value based on the antecedent 5-d rainfall amount and the corresponding S-value from equation (3.7) is used in equation (3.6) for computing the rainfall-excess or direct surface runoff.

3.2 RUNOFF CN ESTIMATION

The basic parameter CN of the SCS-CN model requires the watershed characteristics such as, landuse and treatment classes (Agricultural, Range, Forest, and more recently, Urban (SCS, 1986)), Antecedent Moisture Condition (AMC), Hydrologic Soil Group information (A, B, C, and D) and Hydrologic surface condition (Poor, Fair and Good) of a watershed. From the error analysis, Hawkins (1975) pointed out that the errors in CN may have much more serious consequences than errors of similar magnitude in P, but for a considerable precipitation range (up to about 9 inches). Thus, it is clearly understood that the accurate CN estimation is of significant importance in storm runoff calculation.

3.3 HYDROLOGIC SOIL-COVER COMPLEX NUMBER PROCEDURE

This method primarily needs the watershed characteristics such as landuse and soil type. According to National Engineering Handbook-4 (NEH-4), these soil types were broadly classified into four Hydrologic Soil Groups: A, B, C, and D: 1) 'A' Soils having high infiltration rates, even when thoroughly wetted and consisting chiefly of deep, well to excessively drained sands or gravels. These soils have a high rate of water transmission. 2) 'B' Soils having moderate infiltration rates when thoroughly wetted and consisting chiefly of moderately deep to deep, moderately fine to moderately coarse textures. These soils have a moderate rate of water transmission. 3) 'C' Soils having slow infiltration rates when thoroughly wetted and consisting chiefly of soils with a layer that impedes downward movement of water, or soils with moderately fine to fine texture. These soils have a slow rate of water transmission. 4) 'D' Soils having very slow infiltration rates when thoroughly wetted and consisting chiefly of clay soils with a high swelling potential, soils with a permanent high water table, soils with a clay pan or clay layer at or near the surface, and shallow soils over nearly impervious material. These soils have a very slow rate of water transmission.

SCS developed soil classification system that consists of four groups, which are identified by the letters A, B, C and D. Soil characteristics that are associated with each groups are:

Group A. Under this category soils has a low runoff potential due to high infiltration rates even when saturated (7.6 mm/hr to 11.4 mm/hr). These soils primarily consist of deep sands, deep loess, and aggregated silts.

Group B. Such soils have a moderately low runoff potential due to moderate infiltration rates when saturated (3.8 mm/hr to 7.6 mm/hr). These soils primarily consist of moderately deep to deep, moderately well to well drained soils with moderately fine to moderately coarse textures (shallow loess, sandy loam).

Group C. Soil of this category have a moderately high runoff potential due to slow infiltration rates (1.3 mm/hr to 3.8 mm/hr if saturated). These soils primarily consist of soils in which a layer near the surface impedes the downward movement of water or soils with moderately fine to fine texture such as clay loams, shallow sandy loams, soils low in organic content, and soils usually high in clay.

Group D. Such soils have a high runoff potential due to very slow infiltration rates (less than 1.3 mm/hr if saturated). These soils primarily consist of clays with high swelling potential, soils with permanently high water tables, soils with a clay pan or clay layer at or near the surface, shallow soils over nearly impervious parent material such as soils that swell significantly when wet or heavy plastic clays or certain saline soils.

3.4 COVER TYPE

The most cover types are vegetation, bare soil and impervious surface. There are a number of methods for determining cover types. The most common are field reconnaissance, aerial photograph and land use map.

3.5 HYDROLOGIC CONDITION

Hydrologic condition indicates the effects of cover type and treatment for infiltration and runoff and is generally estimated from density of plant and residue cover on sample areas. Good hydrologic condition indicates that the soil usually has a low runoff potential for that specific hydrologic soil group, cover type, and treatment. Some factors considering the effect of cover on infiltration and runoff are (a) canopy or density of lawns, crops, or other vegetative areas; (b) cover; (c) amount of grass or close-seeded legumes in rotations; (d) percent of residue cover; and (e) degree of surface roughness.

3.6 ANTECEDENT MOISTURE CONDITION

The amount of rainfall in a period of 5 to 30 days preceding a particular storm referred to as antecedent rainfall and the resulting condition in regards to potential runoff is referred to as an antecedent condition. This condition, which is most often, called antecedent moisture condition influences the direct runoff that occurs from a given storm, the effect of antecedent rainfall may also be influenced by infiltration and evapotranspiration during the antecedent period, which in turn affects direct runoff.

To determine the antecedent moisture conditions from data normally available, SCS developed three conditions, which were labeled AMC I, AMC II and AMC III. The soil condition for each is as follows:

1. AMC I represents dry soil with a dormant season rainfall (5-day) of less than 12.7 mm and a growing season rainfall (5-day) of less than 35.56 mm,
2. AMC II represents average soil moisture conditions with dormant season rainfall averaging from 12.7 to 27.94 mm and growing season rainfall from 35.56 to 53.34 mm, and
3. AMC III conditions represent saturated soil with dormant season rainfall of over 27.94 mm and growing season rainfall over 53.34 mm.

Later, depending on the 5-day precipitation amount, AMC II (CN_{II}) is convertible to AMC I (CN_I) or AMC III (CN_{III}) using any of the relations (Table 3.1) given by Sobhani (1975), Chow et al. (1988), Hawkins et al. (1985), and Neitsch et al. (2002), and also directly from the NEH-4 table (SCS, 1972). Here, the subscripts I-III in Table 3.1, and elsewhere in the text refer to AMC I-AMC III, respectively.

Table 3.1. Popular AMC dependent CN-conversion formulae.

Method	AMC I	AMC III
Sobhani (1975)	$CN_I = \dfrac{CN_{II}}{2.334 - 0.01334CN_{II}}$	$CN_{III} = \dfrac{CN_{II}}{0.4036 + 0.005964CN_{II}}$
Hawkins et al. (1985)	$CN_I = \dfrac{CN_{II}}{2.281 - 0.01281CN_{II}}$	$CN_{III} = \dfrac{CN_{II}}{0.427 + 0.00573CN_{II}}$
Chow et al. (1988)	$CN_I = \dfrac{4.2CN_{II}}{10 - 0.058CN_{II}}$	$CN_{III} = \dfrac{23CN_{II}}{10 + 0.13CN_{II}}$
Neitsch et al. (2002)	$CN_I = CN_{II} - \dfrac{20(100 - CN_{II})}{\{100 - CN_{II} + \exp[2.533 - 0.0636(100 - CN_{II})]\}}$	$CN_{III} = CN_{II}\exp\{0.00673(100 - CN_{II})\}$

Chronologically, the AMC-dependent CN-values given by NEH-4 in tabular form were represented by mathematical expressions given independently by Sobhani (1975), Smith and Williams (1980), Hawkins et al. (1985), Chow et al. (1988), and Neitsch et al. (2002). Smith and Williams (1980) developed a relation only for CN_{II} to CN_I, while others provided for both, viz., CN_{II} to CN_I or CN_{III}. According to Mishra et al. (Under review), the Hawkins et al. (1985) CN conversion formulae perform better than others, though there was about 0.1% difference among them all over the range of CN_{II} values from 50 to 100 for either the CN_I or CN_{III} conversions. Here, it is noted that the CN-values obtained for most soil-cover-moisture complexes in the field are generally greater than 40 (SCS, 1972). Therefore, the Hawkins et al. (1985) was recommended for CN-conversion

3.7 CURVE NUMBER

A curve number is an index that represents the combination of hydrologic soil group and land use and land treatment classes. Empirical analysis suggests that the CN was a function of three factors: soil group, the cover complex, and antecedent moisture conditions. The CN-values for different land uses, treatment, and hydrologic conditions are available elsewhere (Singh, 1992; Ponce 1989).

The values of CN for various landuses on the above Hydrological soils can be taken directly from the available standard CN tables (Hydrologic soil-cover complex number) of NEH-4 (SCS, 1993). These CN values of NEH-4 table represent the average median site-CN, which corresponds to the curve that separated half of the plotted P-Q data from the other half for the given site. This is denoted as CN_{II}, where the subscript stands for AMC II, indicating average runoff potential under average wetting condition of the watershed. This CN_{II} can be derived either by the weighted CN approach or weighted Q approach, as below:

3.7.1 Weighted CN approach

In this approach, the CN-values of the respective hydrological-soil cover complex are multiplied with the respective percent areal coverage of the complexes, as follows:

$$CN_{aw} = \frac{\sum_{i=1}^{n}(CN_i * A_i)}{\sum_{i=1}^{n} A_i} \tag{3.8}$$

where CN_{aw} = area-weighted curve number for the drainage basin; CN_i = curve number for each land use-soil group complex; A_i = area for each land use-soil group complex; and n = number of land use-soil group complex in drainage basin. Then, using this weighted CN, the runoff is estimated from Eqs. (3.6) and (3.7).

3.7.2 Weighted Q approach

Here, direct surface runoff (Q) is computed for each sub-areas of a watershed from Eqs. (3.6) and (3.7), utilizing the CN-value derived for respective hydrological-soil cover complex of the sub-area. Finally, the area-weighted Q is computed as below:

$$Q_{aw} = \frac{\sum_{i=1}^{n}(Q_i * A_i)}{\sum_{i=1}^{n} A_i} \tag{3.9}$$

where Q_{aw} = area-weighted runoff for the drainage basin; and Q_i = runoff at each land use-soil group complex.

Obviously, the weighted-Q method is superior to the weighted-CN method, as the former is more rational than the latter for water balance reasons. However, the weighted CN approach is easier to work with the watershed having many complexes or with a series of storms. Mishra and Singh (2003) pointed out that the computed runoff by above two approaches would significantly deviate for a wide range of CNs for various complexes in a watershed. In general, the weighted-CN method is less time consuming, but tends to be less accurate when compared to the actual measured runoff depth. The difference between the two methods is however is insignificant for total CN difference less than 5 and if the rainfall is high in magnitude.

The following two problems are generally encountered in case of the above "Hydrologic soil-cover complex number" procedure:

1. The calculation of "Hydrologic soil-cover complex number" approach is much more sensitive to the chosen CN than it is to the rainfall depths (Hawkins, 1975; Bondelid et al., 1982).
2. It is difficult to accurately select the CNs from the available CN tables (Hawkins, 1984).

This method is generally used for ungauged watersheds and its utility is enhanced with the aid of remote sensing and Geographical Information System (GIS) techniques in distributed watershed modeling. Here, it is worth emphasizing that CN determination from field data is better than that from hydrologic soil-cover complex number method, as the latter leads to variable, inconsistent or invalid results (Hawkins, 1984).

3.8 Other methods

Due to the SCS-CN method being sensitive to accurate CN estimation for accurate runoff estimation, some researchers tried entirely different approaches. For example, Bonta (1997) evaluated the derived frequency distribution approach for determining watershed CNs from measured data, treating P and Q data as separate frequency distributions. This method gives fewer variable estimates of CN for a wide range of sample sizes than do the methods of asymptotic and Median-CN for CN-estimation. It is advantageous in limited P-Q data situation, and does not require watershed response type to estimate CN, as needed in the asymptotic method. Mishra and Dwivedi (1998) presented an approach to determine the upper and lower bounds or enveloping CNs, which are useful in high and low flow studies, respectively. McCuen (2002) found the quantity (100-CN) to fit the gamma distribution, which he used for developing the confidence intervals for CNs ranging from 65 to 95, with parameter estimation by Method of Moments (MOM). Later, Bhunya et al. (2003) provided a more reliable procedure for estimation of confidence interval by employing the Method of Maximum Likelihood (MOML), and Method of L-moment in addition to MOM as parameter estimation. These methods however require testing on a large data set.

CHAPTER 4

MODEL DEVELOPMENT

To assess the long term (daily) rainfall-surface runoff from catchment, the modified Soil Conservation Services Curve Number (SCS-CN) method (Mishra and Singh, 2002) is used. In the present study, using spatial data in Geographic Information System (GIS), curve number is obtained. Using modified SCS approach, the daily flows have been simulated. These two aspects have been explained in the following section.

4.1 SCS CN METHOD

The major factors that determine the Curve Number are the Hydrologic Soil Group (HSG), Cover type, Treatment and Hydrologic condition of watershed (Chapter 3). These factors can be generated to derive the curve number for a catchment as follows.

4.1.1 Soil Map of the Study Area

The soil of catchment can be classified into hydrologic soil group depending on the permeability and the physical characteristic of the soil (Chapter 3).

4.1.2 Preparation of Landuse Map

The most common spectral index used to evaluate vegetation cover is the Normalized Difference Vegetation Index (NDVI). The basic algebraic structure of a spectral index takes the form of a ratio between two spectral bands Red and near-infrared (NIR). This index is calculated by subtracting Red reflectance from NIR reflectance, and dividing by the sum of the two. For instance, in vegetation areas, the NIR portion of the spectrum is reflected by leaf tissue, and the reflectance is recorded by the sensor. Red light is absorbed by the chlorophyll present in the leaf tissue, thus reducing the reflectance of red light detected at the sensor. This contrast of reflectance and absorption by vegetation cover allows us to evaluate the amount of vegetation present on the surface. The index can be calculated as follows (Rouse et al. 1974):

$$\mathrm{NDVI} = \frac{\mathrm{NIR} - \mathrm{RED}}{\mathrm{NIR} + \mathrm{RED}} \tag{4.1}$$

The NDVI index can range from -1 to +1. Vegetated surfaces tend to have positive values, bare soil may have near zero, and open water features have negative values.

4.1.3 Preparation of Curve Number (CN) Map

The Curve Number Map can be generated by editing the value of landuse map with appropriate Curve Numbers from the table given in NEH- Section 4, or through map calculation operation of landuse map. The derived curve number actually holds for normal antecedent moisture condition (AMC) and it is convertible to dry AMC (or AMC III) for use as an initial value for the start of the proposed model, a description of which follows.

4.2 MODIFIED SCS-CN MODEL

4.2.1 Rainfall-Excess Computation

The modified SCS-CN model can be written for time t as

$$RO_{(t,t+\Delta t)} = \frac{(P_{(t,t+\Delta t)} - I_{a(t)} - F_{c(t,t+\Delta t)})(P_{(t,t+\Delta t)} - I_{a(t)} - F_{c(t,t+\Delta t)} + M_t)}{P_{(t,t+\Delta t)} - I_{a(t)} - F_{c(t,t+\Delta t)} + M_t + S_t} \tag{4.2}$$

where M_t is the antecedent moisture amount, prior to the beginning of the storm. Equation (4.2) is valid for $P_{(t,\,t+\Delta t)} \geq (I_{a(t)} + F_{c(t,\,t+\Delta t)})$, $RO_{(t,\,t+\Delta t)} = 0$ otherwise. If $P_{(t,\,t+\Delta t)} \leq I_{a(t)}$, then $F_{c(t,\,t+\Delta t)} = 0$ and $RO_{(t,\,t+\Delta t)} = 0$. If $P_{(t,\,t+\Delta t)} \leq (I_{a(t)} + F_{c(t,\,t+\Delta t)})$, then $F_{c(t,\,t+\Delta t)} = (P_{(t,\,t+\Delta t)} - I_{a(t)})$. Here, $I_{a(t)} = \lambda S_t$.

4.2.2 Soil Moisture Budgeting

The dynamic infiltration component of infiltration (F_d) that occurred during the Δt period can be computed from the water balance equation as

$$F_{d(t,\,t+\Delta t)} = P_{(t,\,t+\Delta t)} - I_{a(t)} - F_{c(t,\,t+\Delta t)} - RO_{(t,\,t+\Delta t)} \tag{4.3}$$

which is valid for $RO_{(t,\,t+\Delta t)} \geq 0$, $F_{d(t,\,t+\Delta t)} = 0$ otherwise. The term $F_{d(t,\,t+\Delta t)}$ also represents an increase in the amount of soil moisture in the soil profile during Δt period, which when added to its antecedent moisture M_t leads to the antecedent moisture amount for the next storm as:

$$M_{(t,\,t+\Delta t)} = F_{d(t,\,t+\Delta t)} + M_t - ET_{(t,\,t+\Delta t)} \tag{4.4}$$

where $M_{(t,\,t+\Delta t)}$ varies from 0 to S_{abs}. S_t can be modified for the next storm by balancing the soil moisture as

$$S_{(t+\Delta t)} = S_t - F_{d(t,\,t+\Delta t)} + ET_{(t,\,t+\Delta t)} \tag{4.5}$$

It is noted that the sum (S_t+M_t) for a watershed represents the absolute potential maximum retention, S_{abs}, which corresponds to the completely dry condition of the soil. It, in turn, represents the maximum possible available void space in the soil. Therefore, it represents the upper bound of S-variation. The minimum value of S is, however, equal to zero.

4.2.3 Computation of Evapotranspiration

The potential evapotranspiration (PET) can be computed using the pan evaporation as:

$$PET_{(t,\, t+\Delta t)} = PANC \times E_{(t,\, t+\Delta t)} \tag{4.6}$$

where PANC is the pan coefficient and $E_{(t,\, t+\Delta t)}$ is the pan evaporation during Δt period. Pan evaporation depends on several meteorological factors such as temperature, humidity, wind speed, solar radiation, etc. PANC depends on the vegetative cover and season, and thus, is a function of the time of the year. It can be computed as follows:

Assuming that the potential evaporation from the upper soil layer is equivalent to the pan evaporation, $E_{(t,\, t+\Delta t)}$, under the condition of the ample amount of water availability, the actual evaporation, $E_{a(t,\, t+\Delta t)}$, can be computed following Schaake et al. (1996) as:

$$E_{a(t,t+\Delta t)} = E_{(t,t+\Delta t)}\left(1-\frac{S_t}{S_{abs}}\right) \tag{4.7}$$

The Schaake et al. model assumes a 2-layer (upper and lower) storage model, similar to the concept of the Tank model. The potential evapotranspiration from the lower level is computed as

$$PET_{(t,\, t+\Delta t)} = E_{(t,\, t+\Delta t)} - E_{a(t,\, t+\Delta t)} \tag{4.8}$$

A combination of equations (4.7) and (4.8) yields

$$PET_{(t,t+\Delta t)} = \frac{S_t}{S_{abs}} E_{(t,t+\Delta t)} \tag{4.9}$$

A comparison of equation (4.9) with equation (4.6) leads to

$$PANC = \frac{S_t}{S_{abs}} \tag{4.10}$$

Thus, PANC is defined as the ratio of the potential maximum retention at a time t to the absolute potential maximum retention. Following Schaake et al. (1996) further with the assumption that the ratio of moisture deficits for both the upper and lower layers is equal to each other leads to a description of the total amount of evapotranspiration (ET) as

$$ET_{(t,t+\Delta t)} = E_{(t,t+\Delta t)}[1-(S_t / S_{abs})^2] \tag{4.11}$$

or

$$ET_{(t,t+\Delta t)} = E_{(t,t+\Delta t)}[1-(PANC)^2] \tag{4.12}$$

The initial abstraction coefficient, λ, is taken equal to PANC, which varies from 0 to 1.

4.3.4 Catchment Routing

The daily rainfall-excess rates computed using equation (4.2) are routed through the watershed using the single linear reservoir technique. Accordingly, the continuity and storage equations are written, respectively, as:

$$RO - DO = \Delta V/\Delta t \tag{4.13}$$

and

$$V = K\,(DO) \tag{4.14}$$

where V is the reservoir storage or the rainfall-excess detention storage, K is the storage coefficient, Δt is the time interval, RO is the rainfall-excess rate, and DO is the outflow or runoff rate at the outlet of the watershed. Using a finite difference scheme, DO at different time steps can be computed as:

$$DO_{(t+\Delta t)} = d_0\, RO_t + d_1\, RO_t + d_2\, DO_t \tag{4.15}$$

where, t and t+Δt are the time steps at Δt interval (which equals 1-d in daily simulation), and d_o, d_1, and d_2 are the constants expressible as:

$$d_0 = \frac{\Delta t / K}{2 + \Delta t / K} \tag{4.16}$$

$$d_1 = d_0 \tag{4.17}$$

$$d_2 = \frac{2 - \Delta t / K}{2 + \Delta t / K} \tag{4.18}$$

where, t and t+Δt are the time steps at Δt time intervals (which equals 1-d in daily simulation).Here, any other suitable method can also be applied. The method of single linear reservoir is adhered to for simplicity reasons.

4.3.5 Baseflow Computation

It is known that infiltration depends on rainfall. Therefore, if $P-I_a$ is less than F_c on a given day, then $F_c = P-I_a$. It is emphasized that under such a situation, $RO_t = 0$ or $F_{d(t)} = 0$. It implies that F_c exists even prior to the satisfaction of the capillary demands, which is in contrast with reality. This is because of the assumed equivalence between f_c and the minimum infiltration rate at a time approaching infinity,considering that the water infiltrating after saturation through F_c percolates down to meet the water table and finally appears at the outlet of the basin. It further assumes that the basin boundary coincides with the aquifer boundary and no lateral flow contributes to the water table from across the defined watershed boundary. Thus, applying equations (4.13) through (4.14), baseflow (O_b) can be computed as

$$O_{b(t+\Delta t)} = g_0\, F_{c(t)} + g_1\, F_{c(t)} + g_2\, O_{b(t)} \tag{4.19}$$

where

$$g_0 = \frac{\Delta t / K_b}{2 + \Delta t / K_b} \tag{4.20a}$$

$$g_1 = g_0 \tag{4.20b}$$

$$g_2 = \frac{2 - \Delta t / K_b}{2 + \Delta t / K_b} \tag{4.20c}$$

In equations (4.20a-c), K_b is the baseflow storage coefficient [T] and g_0, g_1, g_2 are the base flow routing coefficients.

Thus, the total runoff hydrograph, O, appearing at the outlet of the catchment is computed as the sum of the routed rainfall-excess, DO, and the baseflow, O_b. Expressed mathematically,

$$O_t = DO_t + O_{b(t)} \tag{4.21}$$

Which actually represents the computed total runoff hydrograph.

4.4 PARAMETER ESTIMATION

Model parameters, S_0 [L], F_c [L], K[T] and K_b [T] can be determined using the Marquardt algorithm of constrained least squares. Although these parameters can be determined by trial and error for obtaining the maximum efficiency, it is possible to derive these parameters physically or from rainfall runoff data. Parameter S_0 corresponds to the spatially averaged absolute potential maximum retention and approximates the S value derived for AMC I using usual NEH-4 tables utilizing various watershed characteristics. Parameter F_c represents the product of the spatially averaged final infilteration rate, f_c, and the storm duration, which, for example, is 1 day for daily simulation. Thus, F_c can be derived from given soil types of the watershed. Parameter K represents the storage coefficient of the surface runoff hydrograph and is analogous to the time lag of the watershed. It can also be derived from the rainfall-runoff data by plotting them on a semi logarithmic paper. The slope of the fit represents K. The rainfall-runoff data set selected for the derivation should correspond to high rainfall-runoff events excluding baseflow. Similarly, parameter K_b, which represents the time lag of the baseflow appearing at the outlet of the watershed can be derived for low rainfall-runoff events or using other methods suggested in standard texts, for example in the textbooks by Ponce (1989), Singh (1992) and Singh and Singh (2001), among others.

For describing the range of variation of these parameters, the lower bound can be taken as zero, because all the parameters are physically non-negative. The upper bound values can, however, be decided from trial runs whether the estimated parameters values are well within the supplied range. If the estimated parameters value corresponds to the upper bound of the described range, the upper bound is increased to the extent that the estimates fall in the prescribed range.

4.5 MODEL CALIBRATION

Model calibration in general involves manipulation of a specific model to reproduce the response of the catchment under study within some range of accuracy. In a calibration procedure estimation is made of the parameters, which cannot be assessed directly from field data. All empirical (black box) models and all lumped, conceptual models contain parameters whose values have to be estimated through calibration. The fully distributed physically-based models contain only parameters which can be assessed from field data, so that in theory a calibration should not be necessary if sufficient data are available. However, for all practical purposes the distributed, physically-based models also require some kind of calibration, although the allowed parameter variations are restricted to relatively narrow intervals compared with those for the empirical parameters in empirical or lumped, conceptual models.

In principle three different calibration methods can be applied:

a. 'Trial and Error', manual parameter assessment

b. Automatic, numerical parameter optimization

c. A combination of (a) and (b)

The trial and error method implies a manual parameter assessment through a number of simulation runs. This method is by far the most widely used and is the most recommended methods, especially for the more complicated models. A good graphical representation of the simulation results is a prerequisite for the trial and error method. An experienced hydrologist can usually achieve a calibration using visual hydrograph inspection within 5-15 simulation runs.

Combination of the trial and error and automatic parameter optimization method could involve, for example, initial adjustment of parameter values by trial and error to delineate rough orders of magnitude, followed by fine adjustment using automatic optimization within the delineated range of physically realistic values. The reverse procedure is also possible, first carrying out sensitivity tests by automatic optimization to identify the important parameters and then calibrating them by trial and error. The combined method can be very useful but does not yet appear to have been widely used in practice.

Finally, given the large number of parameters in a physically based distributed model like the SHE model, it is not realistic to obtain an accurate calibration by gradually varying all the parameters one by one or in combination. A more sensible approach is to attempt a coarser simulation using only the few parameters to which the simulation is most sensitive, which is derivable from sensitivity analysis. However, experience suggests that the soil parameters will usually require the most attention because of their role in determining the amount of precipitation which infiltrates and hence the amount which forms overland flow.

The above methods of calibration consider single objective function. In case multi objective function is required to be considered, then two types of approaches, viz. classical approach and Pareto approach may be utilized. In classical approach a combined objective function is desired assigning the weights to the various objective function depending upon the user requirement. In Pareto approach a set of parameter values is determined using a search algorithm in such a way that the global optima is achieved considering the multi objective function.

4.6 GOODNESS OF FIT AND ACCURACY CRITERIA

In calibration an accuracy criterion can be used to compare the simulated and measured outputs. This enables an objective measure of the goodness of fit associated with each set of parameters to be obtained and the optimum parameter values to be identified. However, selection of an appropriate criterion is greatly complicated by the variation in the sources of error discussed in the last section. It further depends on the objective of the simulation (e.g. to simulate flood peaks or hydrograph shape) and on the model output variable, e.g. phreatic surface level, soil moisture content, and stream discharge or stream water level. No single criterion is entirely suitable for all variables and even for a single variable it is not always easy to establish a satisfactory criterion. Hence a large number of different criteria have been developed. The most widely used criterion is the sum of the squares of the deviations between recorded and simulated F^2-value of a variable:

$$F^2 = \sum_{i=1}^{n} (QOBS_i - QSIM_i)^2 \qquad (4.22)$$

where, F^2 = index of disagreement, or objective function

$QOBS_i$ = recorded value at time step i

$QSIM_i$ = simulated value at time step i

n = number of values (time steps) within the considered time period

All values of $QOBS_i$ and $QSIM_i$ are based on a time step, which may be one hour, one day or one month. One disadvantage with this criterion is that F^2 is dimensional (e.g. $(m/s)^2$). Therefore, the following nondimensional form is often used:

$$R^2 = \frac{\frac{1}{n}\sum_{i=1}^{n}(QOBS_i - \overline{QOBS})^2 - \frac{1}{n}\sum_{i=1}^{n}(QOBS_i - QSIM_i)^2}{\frac{1}{n}\sum_{i=1}^{n}(QOBS_i - \overline{QOBS})^2} \qquad (4.23)$$

$$(\overline{QOBS}) = \frac{1}{n}\sum_{i=1}^{n} QOBS_i \qquad (4.24)$$

where R^2 is often denoted the coefficient of determination, the explained variance or the model efficiency. R^2 can vary from 0 to +1, where R^2 = +1 represents a complete agreement between recorded and simulated values. It is noted that the simple one parameter model $QSIM_i$ = QOBS will give R^2=0. Although the R^2 criterion is a dimensionless measure it depends heavily on the variance in the recorded series. Thus comparison of R^2 values for different catchments or even for different periods in the same catchment makes no sense.

Among the other numerical criteria often used are the following:

$$F = \sum_{i=1}^{n} \left|(QOBS_i - QSIM_i)\right| \qquad (4.25)$$

Which is a measure of the accumulated deviation (absolute) between recorded and simulated values;

$$F^{2\log} = \sum_{i=1}^{n} (\log QOBS_i - \log QSIM_i)^2 \qquad (4.26)$$

$$R = \frac{\sum_{i=1}^{n} (QOBS_i - \overline{QOBS})(QSIM_i - \overline{QSIM})}{\sum_{i=1}^{n} (QOBS_i - \overline{QOBS})^2 \sum_{i=1}^{n} (QSIM_i - \overline{QSIM})^2} \qquad (4.27)$$

Which does not focus as much on peak matching as does the F^2 criterion; and it is the linear correlation coefficient between the simulated and the recorded series:

It is perfectly feasible to calibrate a model by optimizing just one of the available criteria. However, a calibration based on 'blind' optimization of single numerical criterion risks producing physically unrealistic parameter values, which, if applied to a different time period, will give poor simulation results. In the same vein it should be remembered that the criteria measure only the correctness of the estimates of the hydrological variables generated by the model and not the hydrological soundness of the model relative to the processes being simulated. It is therefore recommended that, in a calibration, numerical criteria be used for guidance only. In general it is recommended that a combination of the following four conditions be considered in determining goodness of fit:

1. A good match between average simulated and recorded flows and good water balance.

2. A good agreement for the peak flows, with respect to volume, rate and timing.
3. A good agreement for low peaks.
4. A good overall agreement for hydrograph shape with emphasis on a physically correct model simulation.

These four conditions can be optimized numerically or subjectively through interactive computer graphics. In cases where all four criteria cannot be optimized simultaneously the priority depends on the objective of the project in question. Finally, although the use of numerical criteria has been emphasized above, the value of graphical comparison of simulated and observed hydrograph should not be overlooked. Although analyzed more subjectively, a graphical plot provides a good overall impression of the model capabilities is easily assimilated and may yield more practical information than does a statistical function. Graphical comparison should always be included in any examination of the goodness of fit of a simulated hydrograph.

4.7 MODEL VALIDATION

If the model contains a large number of parameters it is nearly always possible to produce a combination of parameter values, which permits a good agreement between measured and simulated output data for a short calibration period. However, this does not guarantee an adequate model structure or optimal parameter values. The calibration may have been achieved purely by numerical curve fitting without considering whether the parameter values so obtained are physically reasonable. Further, it might be possible to achieve multiple calibrations or apparently equally satisfactory calibrations based on different combinations of parameter values. In order to find out whether a calibration is satisfactory, or which of several calibrations is the most correct, the calibration should therefore be tested (validated) against data different from those used for the calibration (e.g. Stephenson and Freeze, 1974). According to Klemes (1986), a simulation model should be tested to show how well it can perform the kind of task for which it is intended. Performance characteristics derived from the calibration data set are insufficient as evidence of satisfactory model operation. Thus the validation data must not be the same as those used for calibration but must represent a situation similar to that to which the model is to be applied operationally.

CHAPTER 5

STUDY AREA AND DATA AVAILABILITY

The study area chosen for the present study is a part of Sutlej basin falling between Rampur and Kasol in Himachal Pradesh (India), as described below.

5.1 DESCRIPTION OF SUTLEJ BASIN

5.1.1. General

Sutlej River is a major river of the Indus System, which originates from Mansarovar Lake in Tibet. The catchment of the river upto Bhakra Dam site lies between North latitudes 30°45' and 31°45' and East longitudes 76°15' and 78°. It enters India near Shipkila at an elevation of about 2,530 m and continues to flow in Himachal Pradesh through Wangtoo and Kian before reaching Bhakra Dam. The principle tributaries of Sutlej below Shipkila are the Spiti, Kashming, Baspa, Bhaba, Nogli, Korpan, Nauti, Sholding, Seer, Bharari, Ali and Ghamber Khad.

The total catchment area of the Sutlej up to Bhakra Dam site is about 56875-sq. km., out of which about 19975 sq. km. lies in India. The total catchment area of Sutlej River from Rampur to Kasol is about 2785 sq. km. In the present study, this part of the catchment, i.e. from Rampur to Kasol, has been chosen and it is shown in Figure 5.1.

5.1.2 Topography

The fall of Sutlej from its source to the planes of India is reasonably uniform, the height of the bed is about 4570m near Lake Mansarovar, 2530m near Shipkila, 915m near Rampur, 460m near Bilaspur and 350m near Bhakra Dam site. A gross fall of 2180m is available in the river bed from Shipkila to Bhakra in a length of about 320km. The valley is narrow in the portion from Shipkila to Pooh and from Thopan to Rampur. In the portion between Pooh to Thopan and between Rampur to Bhakra the valley is comparatively wide. It is widest in the portion immediately upstream of Bhakra.

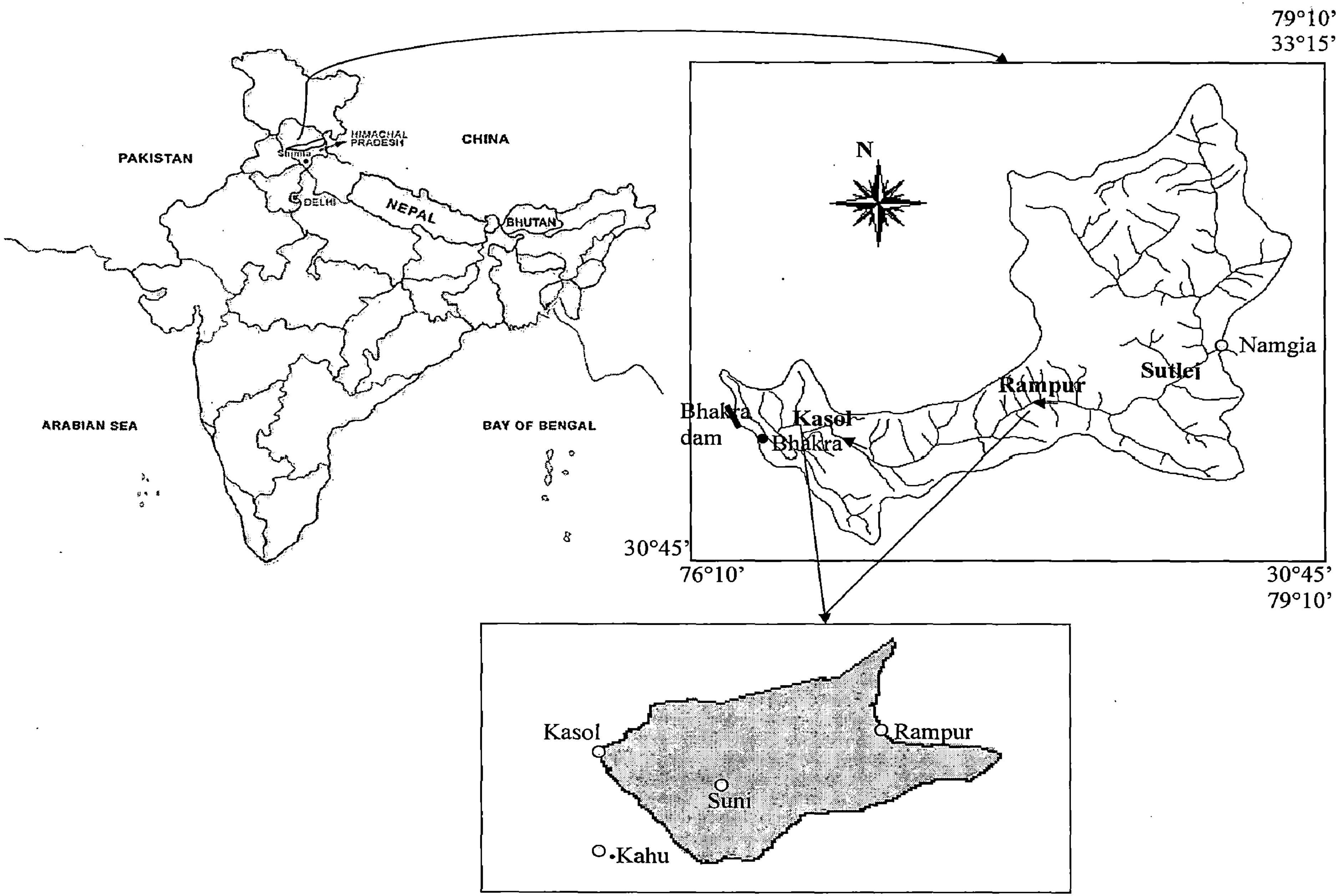

Figure 5.1 Location of the study area with raingauge locations

The bed slope of the river is flat from Shipkila to Jangi Dam site for a distance of about 42-km, which is in the order of 1 in 175. It becomes steep between Jangi Dam site and Rampur, the slope being 1 in 87 and is again flatter from Rampur to Kasol site with a slope of 1 in 300. It is the flattest in the Bhakra reservoir area, the portion downstream of Kasol, where the bed slope is 1 in 500.

5.1.3 GEOLOGY

General geology of the area

Geological mapping of the area by GSI indicates the lithostratigraphic sequence given in Table 5.1.

Table 5.1. Lithostratigraphic Sequence

Formation	**Unit**
Sub-recent	River Terrace Gravels, uncemented to well cemented
Unconformity	
Post-shali	Basic Intrusions Upper Dolomite Pink Limestone
Shali	Lower Dolomite Upper Dolomite Khiara Quartzite Basal Red Shale
Minor Unconformity	
Infra-shali	Trap, Slate, Quartzite, Phyllite

General geology of Catchment

In general the Sutlej River and its tributaries have carved narrow valleys or deep gorges, and the catchment area will be entirely contained within the river valleys. Several of the cultivated low river terraces will be submerged.

The stratigraphic bedrock units exposed in the catchment area consist of three groups:

1. Shali Formation, represented by reddish brown shales, Kharia quartzites, lower colomite, pink limestone and upper dolomite.
2. Basantar Formation represented by brownish to black shales and limestones.
3. Intrusive flows represented mainly by dark green to black basic rocks.

Bed rock along the river, as observed by geological Survey of India (GSI), in general trends N-S to N20^{o} W from the Kasol site to the Kian village, and then changes to NW-SE direction upto the Tattapani area about 7.7 km upstream of the Bashwari Khad.

Overburden in the area consists of a series of granular terraces and shallow depths of colluvium and debris part of bedrock slopes. Several faults of considerable continuity have been identified in the catchment area mainly running parallel to the bedding of the rock units. Close to these faults the rock is generally sheared and heavily broken.

One runs along the contact between the upper dolomite and the basic rock, and other between Khaira quartzite and the lower dolomite unit in front of the Kian terrace. Apparently the most important fault noted in the photogeological study is one trending NW-SE and traced in catchment area from a point about 2.3 km upstream of Jartu up to Annum. The course of the Sutlej River seems to be determined in the area by this fault.

5.2 DATA AVAILABILITY

5.2.1 Hydro-meteorology

The climatic condition of the river basin is largely influenced by the orographic effects. The elevation 1525m is the approximate boundary between areas receiving the majority of precipitation in the form of rain and snowfall. There are three raingauge stations in the catchment area and using Thiesien polygon approach rainfall for the catchment area has been computed. The discharge data is available at Rampur and Kasol site on the River. The effective area between these two sites is 2785 km^2. The runoff for this intermediate catchment was obtained and converted to runoff (mm). In this part of the Sutlej catchment there is no contribution from snowmelt.

The daily rainfall and evaporation data are available from 1988 to 1997. The runoff data is available for the same period. These data has been processed and missing data is filled. This data has been arranged for application in the model.

(a) Rainfall

There are at present twenty raingauge stations in the catchment of Sutlej River upstream of Bhakra, at which long term records are available. Out of which Rainfall data of 4 rain gauge stations situated in the catchment upstream of Kasol to Rampur site is considered.

The annual precipitation pattern is dominated by the monsoon from June to September during which about 48% of the total annual rainfall occurs. In the catchment upstream of Rampur, snowmelt is predominant and in catchment downstream of Rampur the rainfall is predominant. The average rainfall of the four rain gauge stations are given in Table 5.2

(b) Temperature

Some significant temperature data observed at few locations in Table 5.3.

(c) Evaporation

No measurements of evaporation are available for Kasol reservoir area, however, observations have been made at Bhakra which may be considered applicable and given in Table 5.4. This shows that losses due to evaporation are negligible relative to the mean Sutlej River flows.

Table. 5.2. Average rainfall at different rain gauge stations

				MONTHLY AVERAGE RAINFALL AT DIFFERENT RAINGAUGE STATIONS									
		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1988	Rampur	2	150.2	51.4	13	32.4	108.3	217.9	137.6	211.8	0	0	81.9
	Suni	33.8	59.7	106.3	4.2	34.7	90.1	478.4	263.5	228.6	0	0	130.5
	Kasol	13.5	45	101.5	0	14.9	178.9	561	465.8	335.4	0	0	97.3
	Kahu	13.5	45	101.5	0	14.9	178.9	561	465.8	335.4	0	0	97.3
1989	Rampur	4.3	6.6	49.1	21.2	33.8	9.7	156.2	172.3	4.6	8.7	40.2	69.2
	Suni	101.1	26.1	47.5	6.7	79.7	38	252.4	143.9	60.5	0	66	59.7
	Kasol	98.2	19.1	72.3	0	12.1	62.9	322.5	415.1	55	0	57	53.5
	Kahu	98.2	19.1	72.3	0	12.1	62.9	322.5	415.1	55	0	57	53.5
1990	Rampur	69.3	62.2	186.1	54.2	20.1	165.6	145.2	85.7	21.2	3.8	7	131.2
	Suni	4	106.7	166	21	40.9	104.8	263.9	181.1	74.8	4	6	153.4
	Kasol	24	82	99.6	19	47.4	121	437.9	406.6	236.3	0	4.5	181.5
	Kahu	24	82	99.6	19	47.4	121	437.9	406.6	236.3	0	4.5	181.5
1991	Rampur	49.8	109.4	73.3	27.1	14.8	20.3	36	109.6	13.8	0	0	56.5
	Suni	7.1	63.6	34.4	54.9	21.5	60.5	117.7	163.8	29.7	3.8	0	65.9
	Kasol	0	104.8	46.4	60.2	12.8	108	225.9	182.5	97.1	8.8	0.5	62.3
	Kahu	0	104.8	46.4	60.2	12.8	108	225.9	182.5	97.1	8.8	0.5	62.3
1992	Rampur	170	24	70.8	56.5	34.5	79.4	227.9	171.9	8.5	0	10	83.9
	Suni	152.4	55.6	61.2	5	28.2	66.7	198.7	333.4	118.3	9.7	14.7	0
	Kasol	108.9	55.9	42	2	55	134.8	278.3	662.2	90.3	0	18.6	0
	Kahu	108.9	55.9	42	2	55	134.8	278.3	525.4	114.8	2.7	10.7	0
1993	Rampur	29.5	100.4	120	47.9	48.5	156	131.3	117	4	27.6	0	12
	Suni	94.1	51.8	128.6	6.3	50.4	102.9	357	75.9	143	0	13	0
	Kasol	80.2	27.2	75.5	7.8	60.8	127.2	359.9	251.3	127.1	0	2.2	0
	Kahu	59.5	49	82.1	5	20.8	109.1	463.9	123.8	102.7	0	6.5	0
1994	Rampur	107.6	68.2	65	58.1	35.4	97.6	247.6	209.8	11.5	0	0	48.8
	Suni	28.8	118.2	8	55.3	37.5	71	206.7	168.7	117.8	5.5	0	22.8
	Kasol	38.1	115.6	4.6	38.7	31.4	83.7	442.3	607.7	59.5	0.5	0	12.9
	Kahu	0	0	0	0	28	69.4	534.6	428.5	57.3	0	0	0
1995	Rampur	70.5	72	69	20.9	12.7	152	214.6	183.8	0	4.2	31.2	10.5
	Suni	46.2	99.5	67.8	67	2.2	120.3	255.2	210.1	291.3	2	2.2	11.2
	Kasol	35	66.7	64.1	52.7	8.5	44.9	600.7	380.2	173.9	4.2	5.5	5
	Kahu	0	0	26.6	33.9	0	0	0	0	0	0	0	0
1996	Rampur	68.5	80.7	139.4	45	34.1	94.7	103	212.1	15.7	22.3	0	6
	Suni	60.6	78.5	70.8	54.8	57.7	131.4	90	171.3	101.3	11.4	0	3.7
	Kasol	74.4	93.1	51.2	20.6	22.9	300.2	257.5	333.7	142.8	44.2	0	1.5
	Kahu	10	132.2	51.6	20.7	39.5	361.4	214.3	393.3	126	32	0	1.8
1997	Rampur	34.5	16.5	77.2	109	45.7	83.4	280.3	88.6	16.8	58.7	95.2	14.3
	Suni	39	32	44.6	87.1	78	154.8	139.4	256.1	57.9	51.5	78.1	86
	Kasol	46.8	29.5	17.6	114	75.7	107.9	324.9	406.8	254.2	45.2	99	102.9
	Kahu	62.4	34.7	0	0	48.7	85.7	312.6	506.1	291.6	77.7	70.9	105.1

Table 5.3 Maximum and minimum temperature data observed at few locations in the study area

Station	Maximum Temp° C	Minimum Temp° C
Shimla	30	-7.2
Bilaspur	45.5	2.0
Kalpa	27	-9.5

Table.5.4 Evaporation data

Month	Evaporation (mm)
January	50
February	60
March	110
April	190
May	260
June	230
July	130
August	100
September	110
October	100
November	70
December	50
Total	1460
Mean	120

5.2.2. Other Data Used

Data that have been used for study are:

- **Base Map**

Survey of India (SOI) Toposheet No. 53E (scale 1:250,000)

- **Ancillary Data**

  Soil Map (Himachal Pradesh Soils sheet 1 &2) prepared by National Bureau of soil survey and land use planning (ICAR) Nagpur.

Satellite data

In the present study, IRS data have been used.

CHAPTER 6

RESULTS AND DISCUSSION

As described in the previous chapters, an SCS-CN-based long term hydrologic simulation model (Chapter 4) was developed and it is tested on the data of Sutlej river basin (Chapter 5). The proposed model has four model parameters, S_0 [L], F_c [L], K [T] and K_b [T]. The first parameter as such represents the initial value of the potential maximum retention. Since the available data start from January 1988, a value of S_0 is required to be supplied as an initial guess for model run in calibration. Therefore, it is in order to begin the discussion with the computation of this value using remote sensing data. Here, it is worth indicating that the initial values of other parameters were fixed by trial and error considering the maximum efficiency criterion (Chapter 4).

6.1 CATCHMENT CHRACTERISTICS

As discussed in Chapter 5, the study area has loamy and sandy soils, shallow to medium deep depth, and these are well drained to excessively drained. The soils of the Sutlej catchment with their Hydrologic soil groups (HSG) are given in Table 6.1. These soils can be broadly classified as to generally fall in hydrologic soil groups A and B.

Table 6.1. Soil Type and Corresponding HSG

S.No.	Depth	Drainage	Soil Type	Other Features	HSG
1.	Medium deep	Somewhat excessively drained	Fix loamy or coarse loamy soils with loamy surface	-	B
2.	Medium deep	Somewhat excessively drained	Sandy soil with sandy surface	-	B
3.	Shallow	Excessively drained	Sandy skeletal soils with loamy surface	Strong stoniness	A
4.	Shallow	Somewhat excessively drained	Loamy skeletal soils with loamy surface	Stoniness	B
5.	Shallow	Well drained	Coarse loamy soils with	Moderate	B

			loamy surface	stoniness	
6.	Medium deep	Well drained	Fine loamy calcareous soils with loamy surface	-	B
7.	Shallow	Well drained	Fine loamy soils with loamy surface	-	B
8.	Medium deep	Well drained	Coarse loamy soils with loamy surface	-	B
9.	Medium deep	Well drained	Fine loamy soils with loamy surface (loamy skeletal)	-	B
10.	Medium deep	Somewhat excessively drained	Coarse loamy soils with loamy surface	Slight	B
11.	Medium deep	Well drained	Fine loamy soils with loamy surface	-	B
12.	Shallow	Excessively drained	Coarse loamy, calcareous soils with loamy surface	-	A

In the present study, two seasons namely Monsoon and Non-monsoon were considered, and landuse maps generated for both the seasons using "NDVI" classification (Chapter 4). The landuse/landcover image was used as input image for hydrologic soil cover complex. Most part of catchment falling under forest is categorized into two types, dense and open forest with fair hydrologic condition. Next landuse pattern is agricultural land, as it is a hilly area and lies under contour and terraced field with good hydrologic condition. The remaining landuse of catchment consists of pasture, grassland or range continuous forage for grazing with fair hydrologic condition. The landuse pattern of the catchment is given Table 6.2.

Table 6.2. Landuse Pattern of the Catchment.

Period	Landuse		Hydrologic Condition	Curve number (CN)	
				A	B
Monsoon	Agricultural		Good	62	71
	Forest	Open	Fair	43	65
		Dense	Fair	36	60
	Grass land		Fair	49	69
	Snow and water body			99	99
Non-monsoon	Agricultural		Good	62	71
	Forest	Open	Fair	43	65
		Dense	Fair	36	60
	Bare land			77	86
	Snow and water body			99	99

On the basis of soil group and land use, curve number for the catchment was estimated and its average value comes out to be 72 for monsoon season, valid for normal antecedent moisture condition (AMC II), and its corresponding value of potential maximum retention under AMC III is 41.34 mm and it was taken as initial estimate for model run in calibration.

6.2 MODEL CALIBRATION AND VALIDATION

For model calibration and validation, the available nine-year data set of the Sutlej catchment (Chapter 5) is split into two parts. For calibration five years (1988-1993) of data have been considered, and the simulated hydrographs depicting rainfall, runoff computed and observed are shown in Figures 6.1-6.5 for calibration and in Figures 6.6-6.9 for validation. In calibration the data in graph for 1988-89 is from January 1988 to May 1989 and for other years it is from June to May. In validation all the graphs are from January to December. From these figures, it is visible that, in both calibration and validation, the observed and computed values of runoff match fairly well in all the years except 1991-92 in which the deviation is too high, primarily due to the occurrence of low runoff values in this year. Both rising and receding limbs of the simulated hydrographs closely match the observed hydrographs.

Table 6.3 Parameters from simulation of different time period.

No. of Years of data used in simulation	Parameters (Calibration)				
	S_0 (mm)	F_c (mm)	K (days)	K_b (days)	Efficiency (%)
	Initial Estimate				
	41.34	10.0	1.0	10.0	
	Final Estimate				
1	14.96	38.68	1.0	17.14	94.35
2	14.27	73.40	0.10	16.20	90.46
3	14.67	43.33	0.91	15.68	93.46
4	12.27	49.67	0.64	19.99	70.64
5*	12.25	48.87	0.71	19.84	73.84

* used as a calibration set

In calibration, the estimated values of the four model parameters (S_0, F_c, K and K_b) along with their initial values and model efficiencies are given in Table. 6.3. It is apparent from this table that the resulting efficiencies in simulation vary from 70.64 to 94.35%, as the number of years of data varies from 1 – 5 years. Though the efficiencies generally show a decreasing trend with the increase in data length, these are indicative of adequate and satisfactory performance of the proposed model in simulation. Then, taking the parameter values corresponding to five years of data in model calibration (Table 6.3), the model was tested on the remaining four years (1994-1997) data. The resulting efficiency of four years data is 72.22% which indicates a satisfactory model performance.

In all the years, the computed peak runoffs were compared with the observed peak runoff and these are given in Table 6.4. For performance evaluation, the relative error (%) was computed as:

$$\text{Relative error (\%)} = (R_o - R_c)*100/R_o \qquad (6.1)$$

Where R_o and R_c correspond to the observed and computed annual runoff values, respectively. Thus the relative error may take any value ranging from 0 to ∞ depending on the value of R_0. As R_0 approaches zero, the relative error approaches infinity. It is apparent from Table 6.4 that except for the year 1991-1992, in which the percent relative error is 52.96%, the relative error otherwise ranges from 14.88% to 28.53% in other years, indicating a generally satisfactory match of the observed and simulated peak runoff rates. Thus, it can be inferred that, in calibration, the proposed model works well on the data of hilly Sutlej catchment. Here, it is noted the SCS-CN method was originally proposed for agricultural watersheds with flat to mild slopes (Neitsch, et al., 2002), and not for hilly areas. However, in application of SWAT model, Neitsch et al. (2002) provided a slope reduction factor for CN conversion in such situations.

Table 6.4 Observed and computed peak runoff and relative errors

Year	Observed peak runoff (mm/day)	Computed peak runoff (mm/day)	% Relative error
1988-89	7.24	5.83	19.48
1989-90	10.66	8.05	24.48
1990-91	7.71	5.51	28.53
1991-92	3.55	1.67	52.96
1992-93	7.39	6.29	14.88

As also seen from Table 6.3, with the increasing length of data, the values of parameters also vary. For example, the parameter S_0 varies in the range from 12.25 to 14.96 mm, F_c from 38.68 to 73.40 mm, K from 0.1 to 1.0 day, K_b from 15.68 to 19.99 days. Thus, the parameters S_0 and K_b exhibit relatively a narrow range of variation whereas the others show quite a wide range of variation. Here, an attempt is made to correlate these parameter values with the general features of the watershed, as follows.

The parameter S_o which represents the potential maximum retention or, from the volumetric concept (Mishra and Singh, 2003) the space available for moisture storage. A low value of this parameter is indicative of the watershed to have very shallow soil profile, which is consistent with the hilly terrain of the watershed. This value is comparable with that given by above estimation corresponding to CN value of 72 (CN = 86 for AMC III), which comes out to be 41.34 mm, as above. The parameter F_c actually represents the rate of water percolation (through the soil profile) to ground water table. These values exhibiting a wide range of variation are not uncommon in practice. For example, while classifying the hydrologic soils as A, B, C, and D (Chapter 3), McCuen (1982) showed quite a large variation of such rates of infiltration for all types of soils. It is also because the infiltration rates not only depend on the soil texture but also on its structure that describes the arrangement of soil particles. This is the structure that decides the connectivity of pores for ground water flow and, in turn, the hydraulic conductivity. This variation may also be attributed to the actual spatial distribution of the rainfall in the study area. If the most part of rainfall occurs in an area exhibiting low draining capacity (or large infiltration rate) of the soil, the resulting runoff values will be low and, in turn, the resulting F_c value will be low. The reverse holds in the otherwise situation. The parameter K represents the lag time between the occurrence of rainfall and the runoff. In other words, it represents the time lag between the rainfall and runoff. Since the area of the watershed is 2785 sq. km, its slope, the catchment being in hilly terrain, is steep, the lag time can be expected to be low. To verify, in a separate study (Jain, 2001), the lag time for the same basin was computed using Kirpich formula and it was computed less than 1 day, which is in conformity with the resulting K values ranging from 0.1 to 1 day. The parameter K_b actually represents the lag time between the percolated water and its appearance as baseflow at the outlet of the basin. Its values varying from 16 to 20 days which are generally low. However, as expected in the hilly terrain, these values are not much unreasonable.

6.3 VOLUMETRIC STATISTIC

To generally show the yearly water balance of the considered watershed, a yearly volumetric analysis for all the components, such as precipitation, initial abstraction, infiltration, baseflow, evapotranspiration, and total surface runoff, was carried out and its statistics is given in Table 6.5. To compare the model computed yearly runoff values with the observed values; the relative error (Eq. 6.1) was computed. It is apparent from Table 6.2 that these errors for five years range from -0.05 to 0.74%. The sufficiently low values of the error are indicative of the more satisfactory model performance. Here, '+' values indicate that the computed values are lower than the observed ones and vice versa for '-' values. It is also apparent from the table that the low runoff producing year yield relatively high relative errors, largely because of the SCS-CN applicability to high runoff magnitudes.

The above described (more than) satisfactory model performance can be further appreciated in view of (i) the limited number of models parameters (only four), (ii) simplicity, and (iii) no constraints imposed for matching the observed annual runoff volumes. In addition, there is little information available on base flows and the lateral ground water interaction across the basin boundaries.

Table 6.5 Annual volumetric statistics

Year	Rainfall (mm)	Infiltration, F (mm)	Base Flow (mm)	ET (mm)	Runoff (Computed)	Runoff (Observed)	Relative Error (%)
1988-89	1609.08	551.43	544.67	7.91	1094.79	965.36	-0.13
1989-90	1016.68	267.73	267.48	4.79	549.33	411.57	-0.33
1990-91	1138.55	438.12	433.67	5.29	876.66	835.66	-0.05
1991-92	763.91	73.94	74.28	3.06	149.30	570.00	0.74
1992-93	669.12	194.94	191.45	3.02	388.63	432.51	0.10

6.4 SENSITIVITY ANALYSIS

To assess the sensitivity of the above four parameters of the model, a sensitivity analysis is carried out. To this end, the parameters calibrated for the year 1988-93 were varied for evaluating the impact of variation on the computed runoff values (or model performance in terms of efficiency) in calibration. If efficiency increases the computed values come closer to the observed ones, and vice versa if the efficiency decreases with the varying parameter values. However, the purpose of such an analysis lies in distinguishing parameters that are more sensitive, for their cautious and judicious employment in the field.

As shown in Figures 6.10 to 6.13, as expected the efficiency in general decreases if the parameter is either drastically increased or decreased from the calibrated one. All the parameters were changed from 5 to 30%, and the corresponding efficiency computed. The change in efficiency in the four parameters is shown in Figs. 6.10 to 6.13, and these are discussed below.

An increase in the value of parameter S_o resulted efficiencies in the range (73.84, 68.55%) (Fig. 6.10). On the other hand, as the parameter value decreased, the efficiency reduced from 73.84 to 63.13%. It is consistent with above narrow variation of S_0 values with the increasing data length and their small values. From figure 6.11, that parameter F_c appears to be more sensitive than S_0, for the efficiency varies more rapidly with the change in the parameter value by the same extent. It can be seen that the variation of F_c from 5% to 30% leads to change in efficiencies in the range (10, 72.83%), which exhibits a much wider range than that due to S_0. In case of decrease in parameter value, the efficiency changes too much and it reaches as low as 10.65%. Such behavior is consistent with the above description of spatially varying infiltration rates with the changing soils from one place to the other. From Figure 6.12, it is apparent that the efficiency does not change significantly (from 73.79% to 73.73%) with increase and decrease in the K-values by the same (as above) extent. Thus, the parameter K is less sensitive than is S_o and/or F_c. Figure 6.13 shows the variation in efficiency (from 72.28% to 70.61%) with the change in parameter K_b. As also described above, this parameter K_b is apparently less sensitive than F_c, but more sensitive than K and S_o. It is because the watershed for the most part is a hilly catchment and its outflow is largely governed by rainfall excess that is in general influence by F_c and its routing, where K influences most. In brief, the most significant parameter S_0 of the SCS-CN model appears to be the least sensitive to variation, and therefore, this model is more amenable to field applications employing the NEH-4 CN values or the CN values derived using remote sensing data, as above.

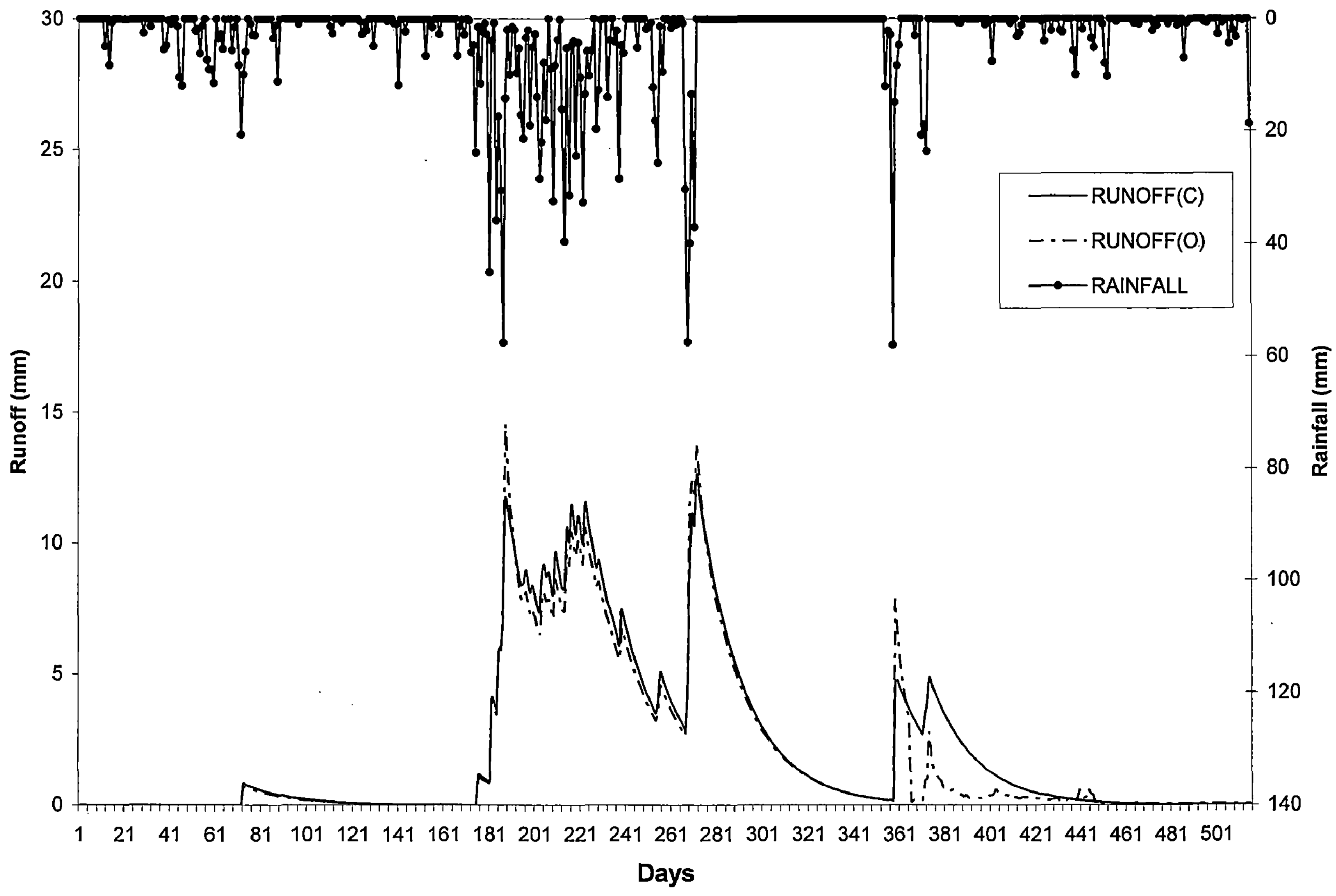

Figure 6.1: Model calibration for Sutlej data (Jan. 1988- May 89). Day 1 represents Jan. 1, 1988.

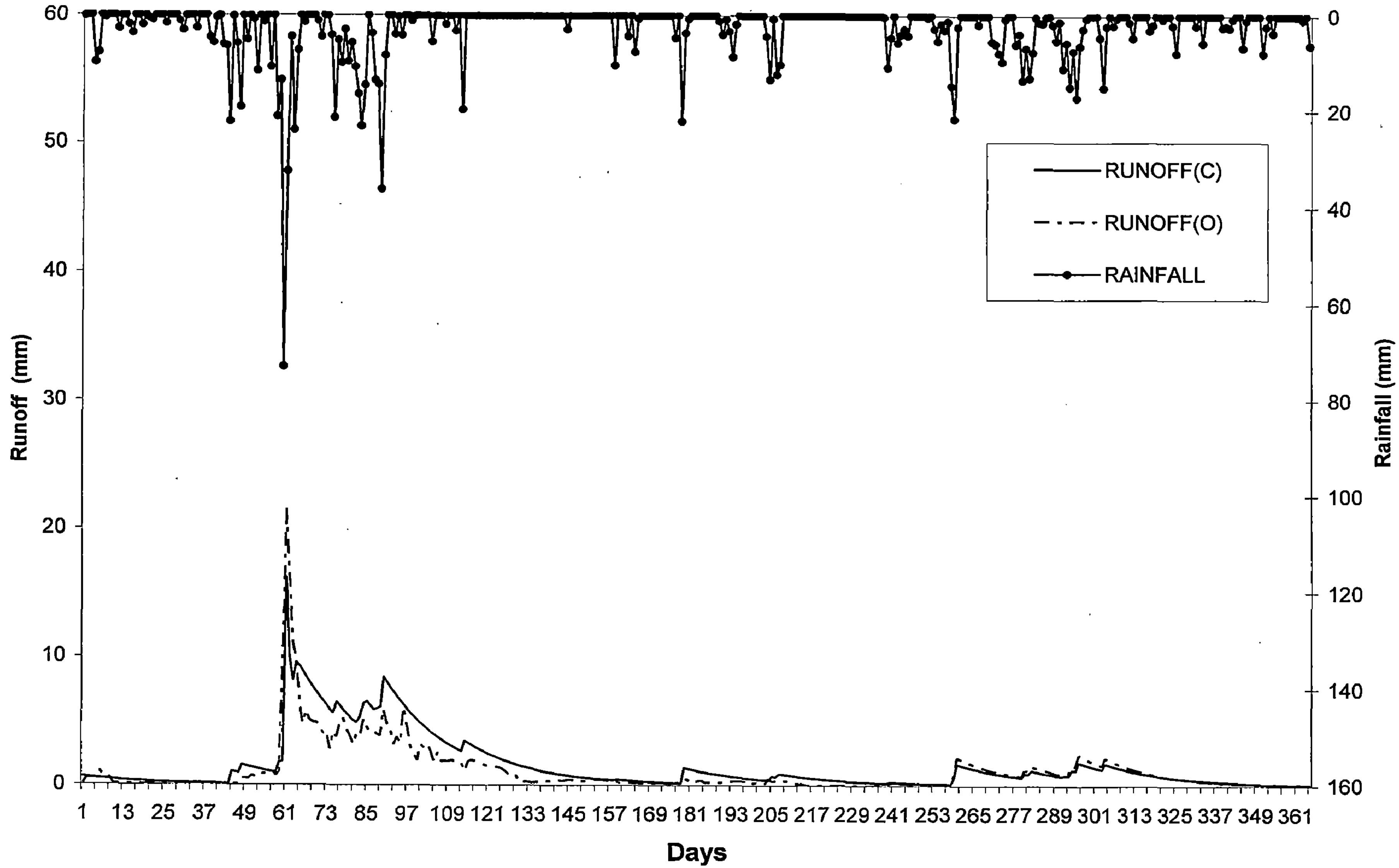

Figure 6.2: Model calibration for Sutlej data (June 1989- May 90). Day 1 represents June 1, 1989.

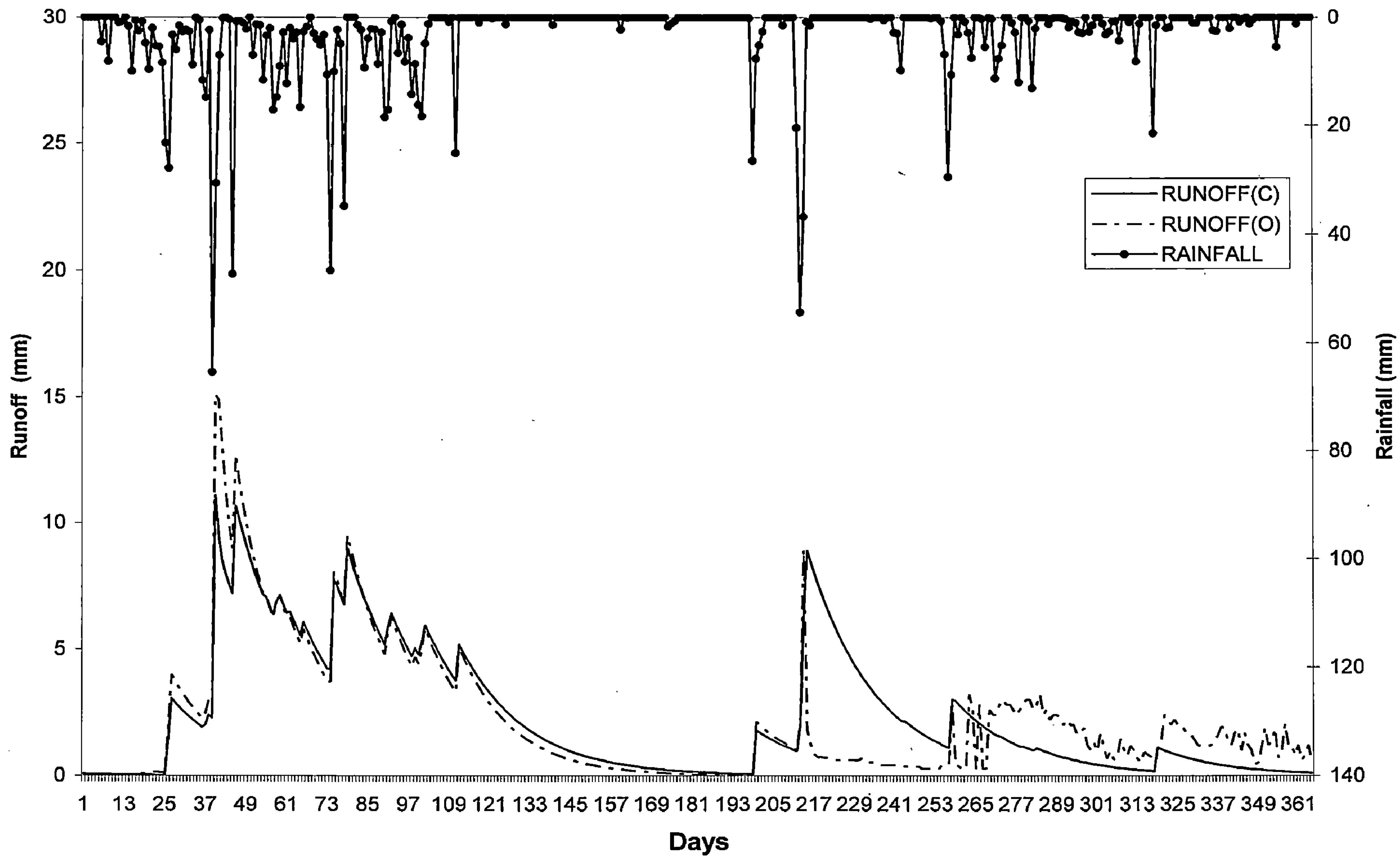

Figure 6.3: Model calibration for Sutlej data (June 1990- May 91). Day 1 represents June 1 1990.

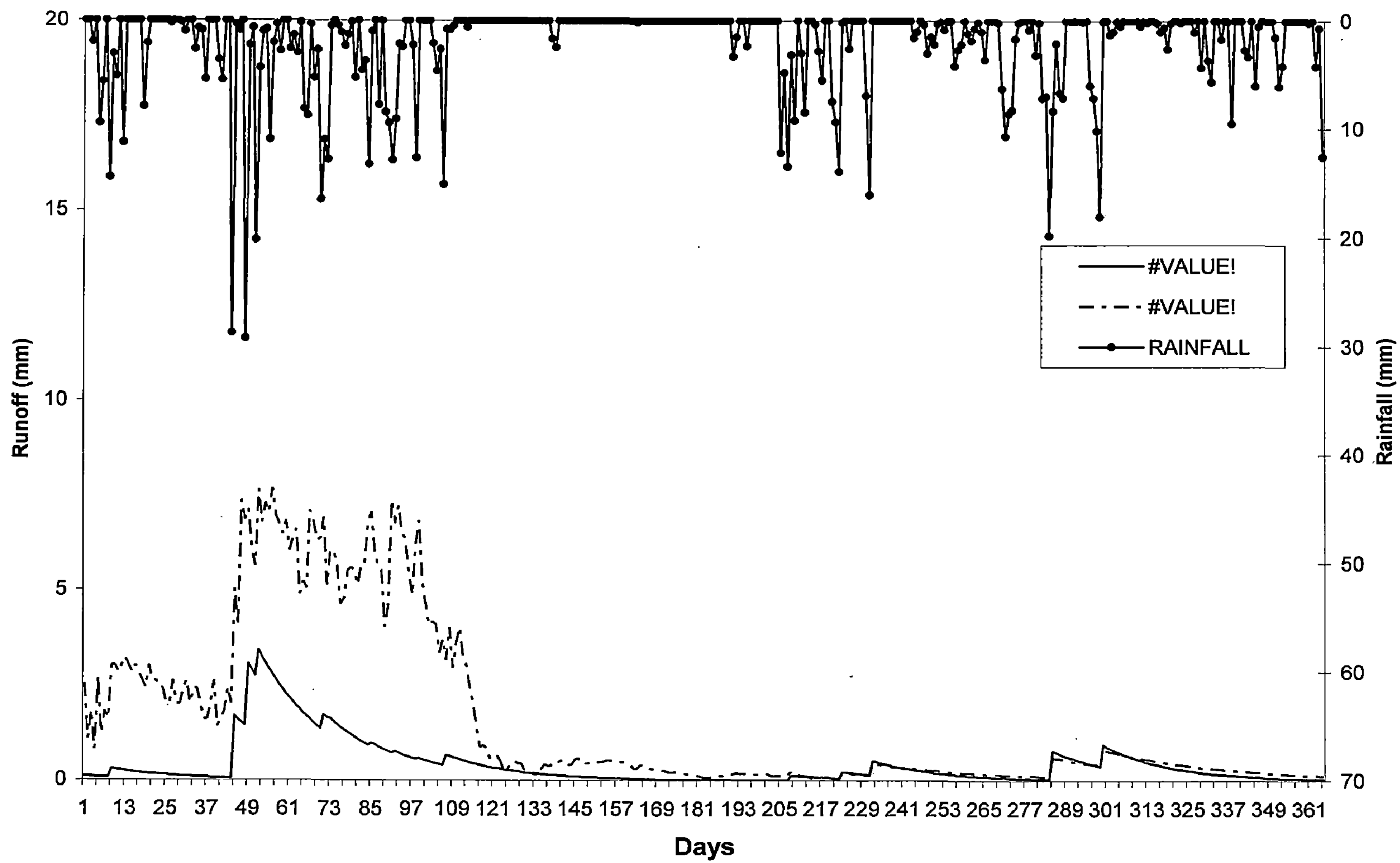

Figure 6.4: Model calibration for Sutlej data (June 1991- May 92). Day 1 represents June 1 1991.

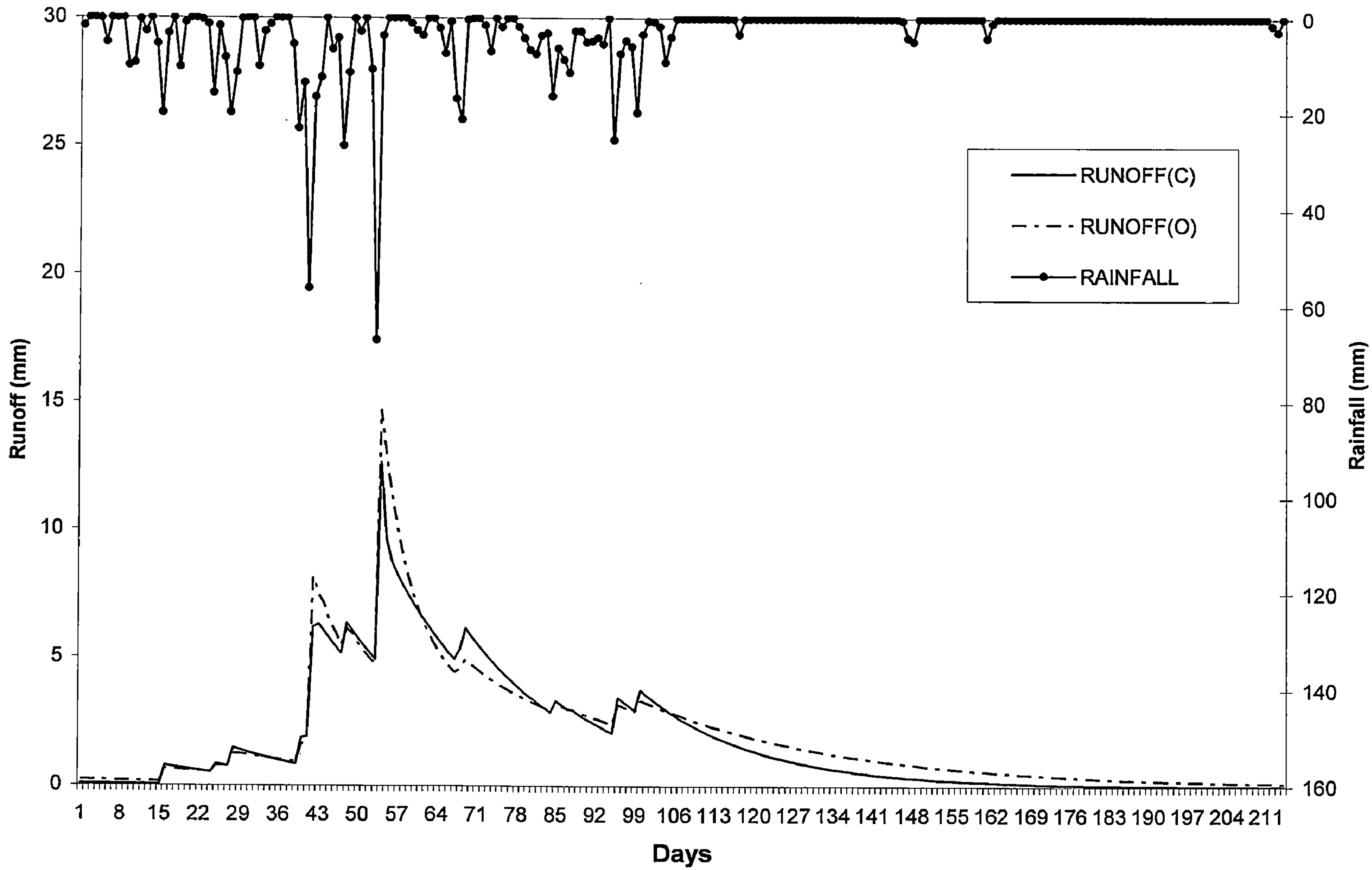

Figure 6.5: Model calibration for Sutlej data (June 1992- May 93). Day 1 represents June 1 1992.

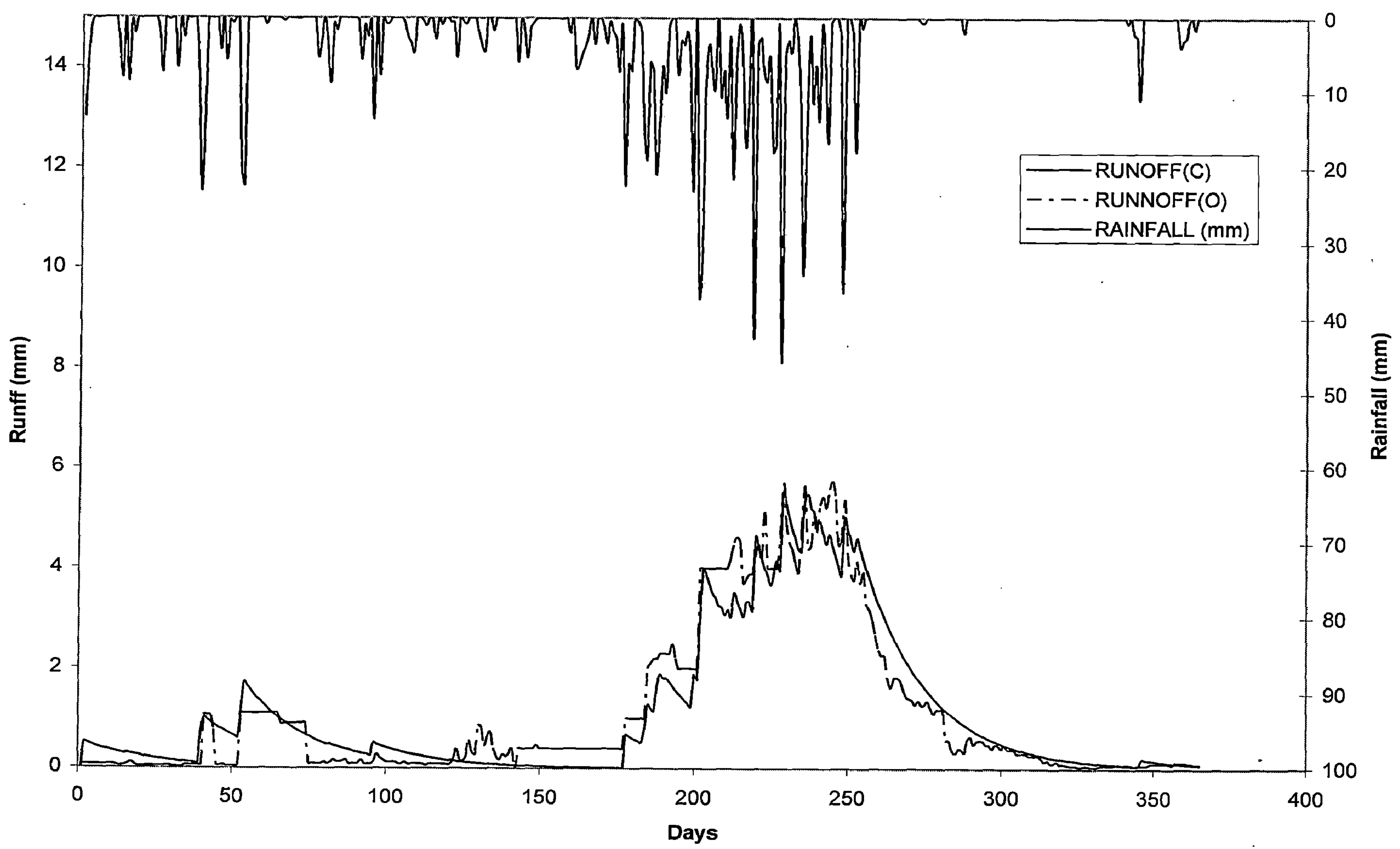

Figure 6.6: Model validation for Sutlej data (Jan. 1994- Dec. 94). Day 1 represents Jan. 1 1994.

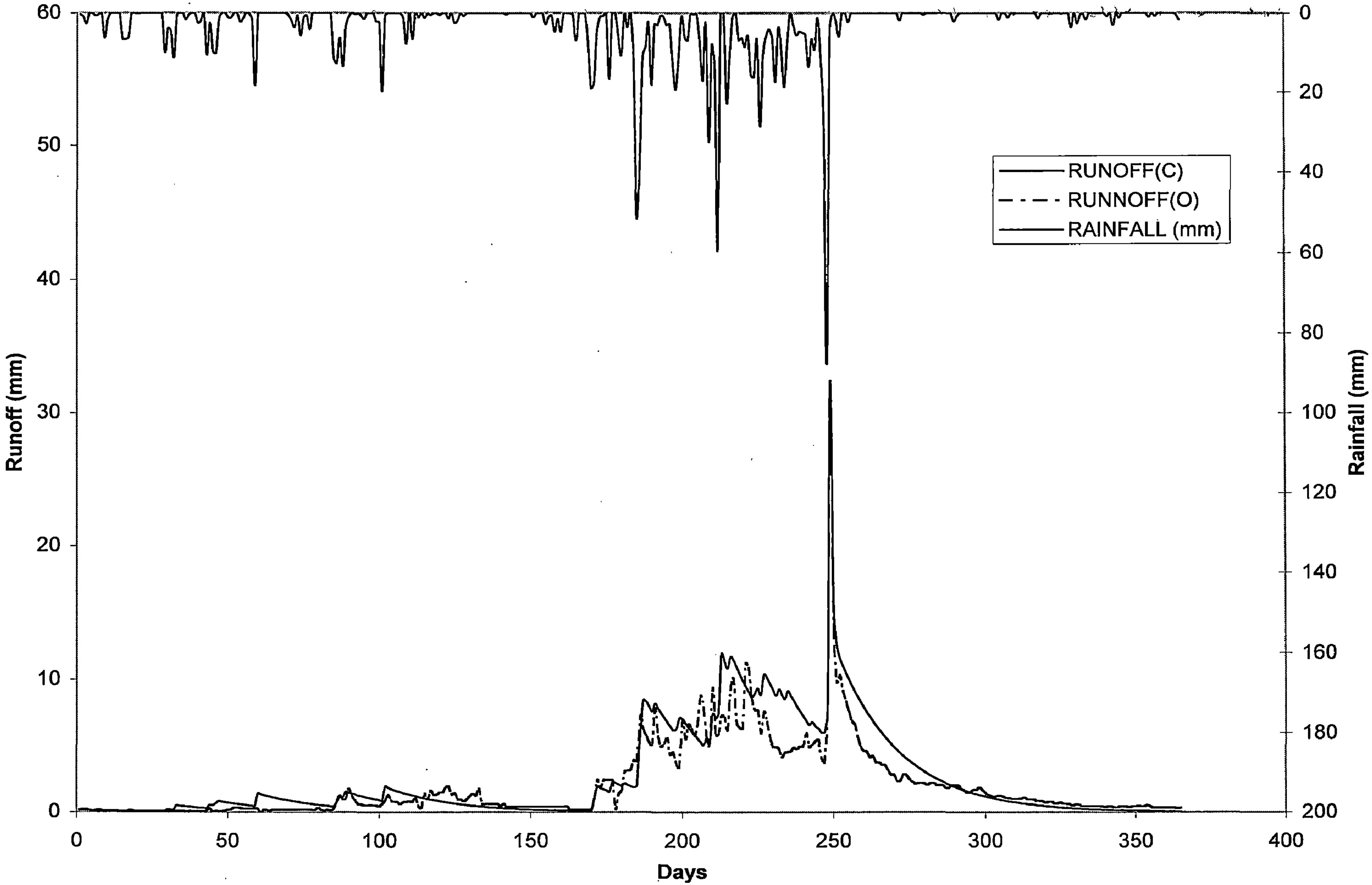

Figure 6.7: Model validation for Sutlej data (Jan. 1995- Dec. 95)

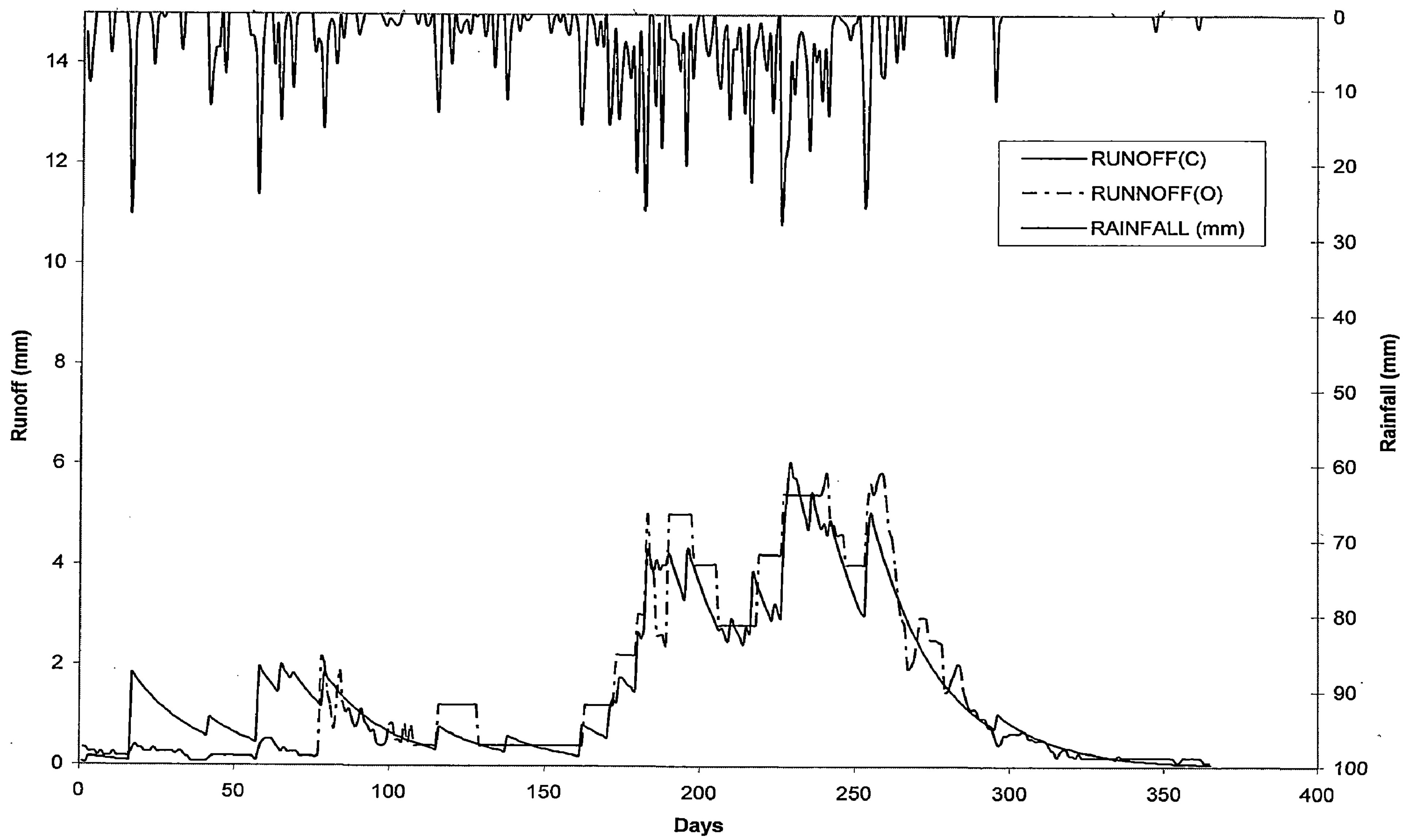

Figure 6.8: Model validation for Sutlej data (Jan. 1996- Dec. 96)

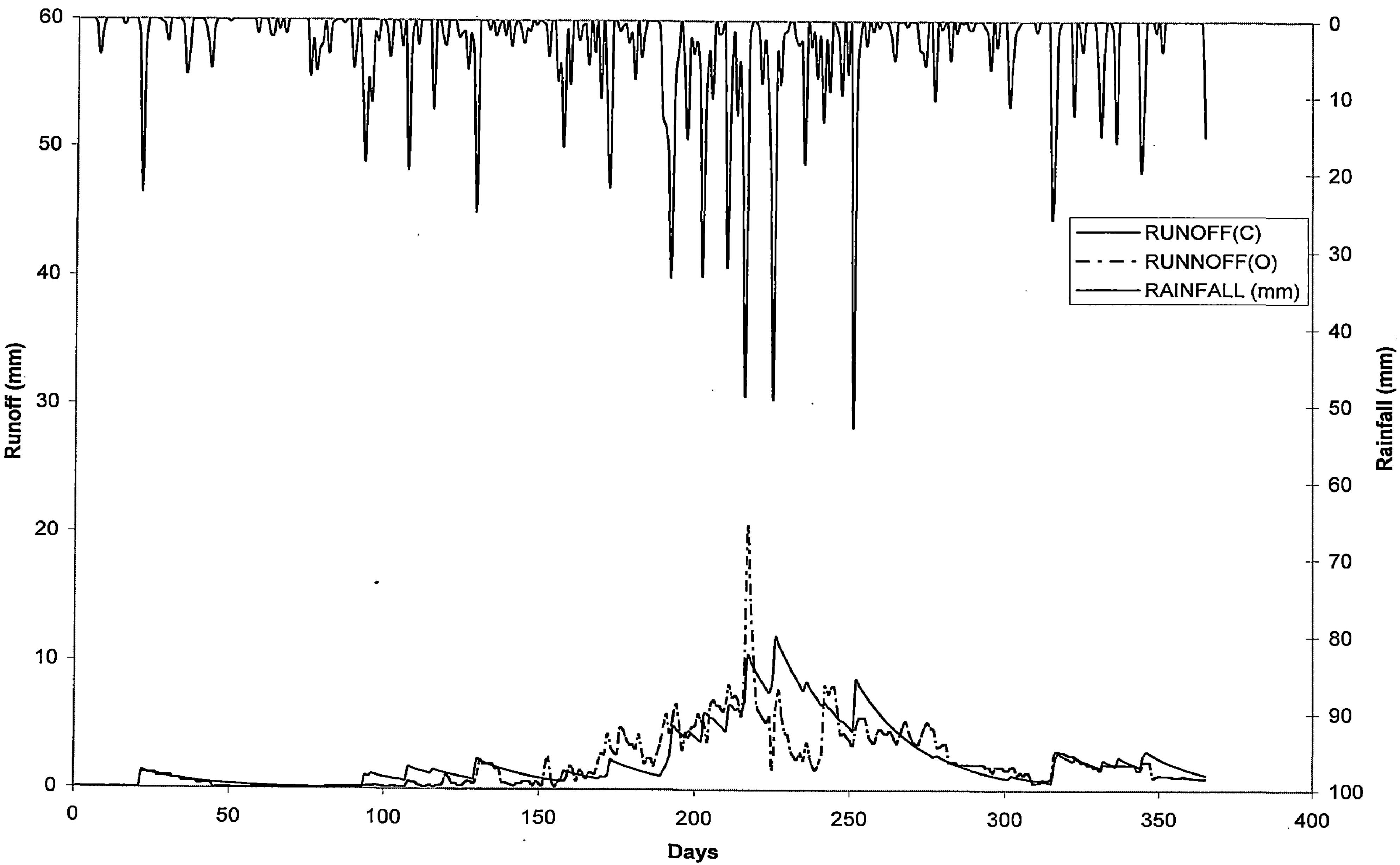

Figure 6.9: Model validation for Sutlej data (Jan. 1997- Dec. 97). Day 1 represents Jan. 1 1997.

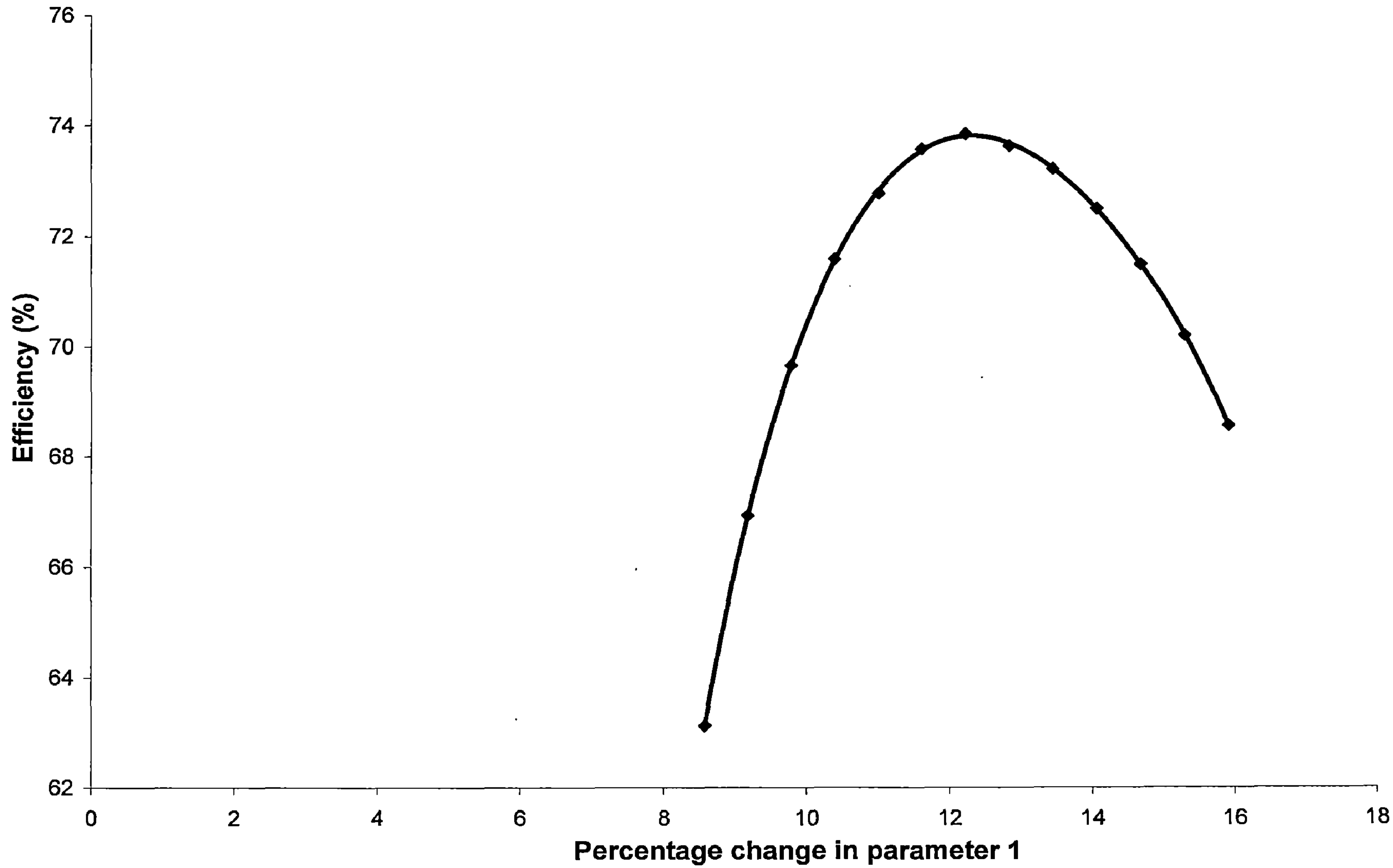

Figure 6.10 Sensitivity of model parameter S_o

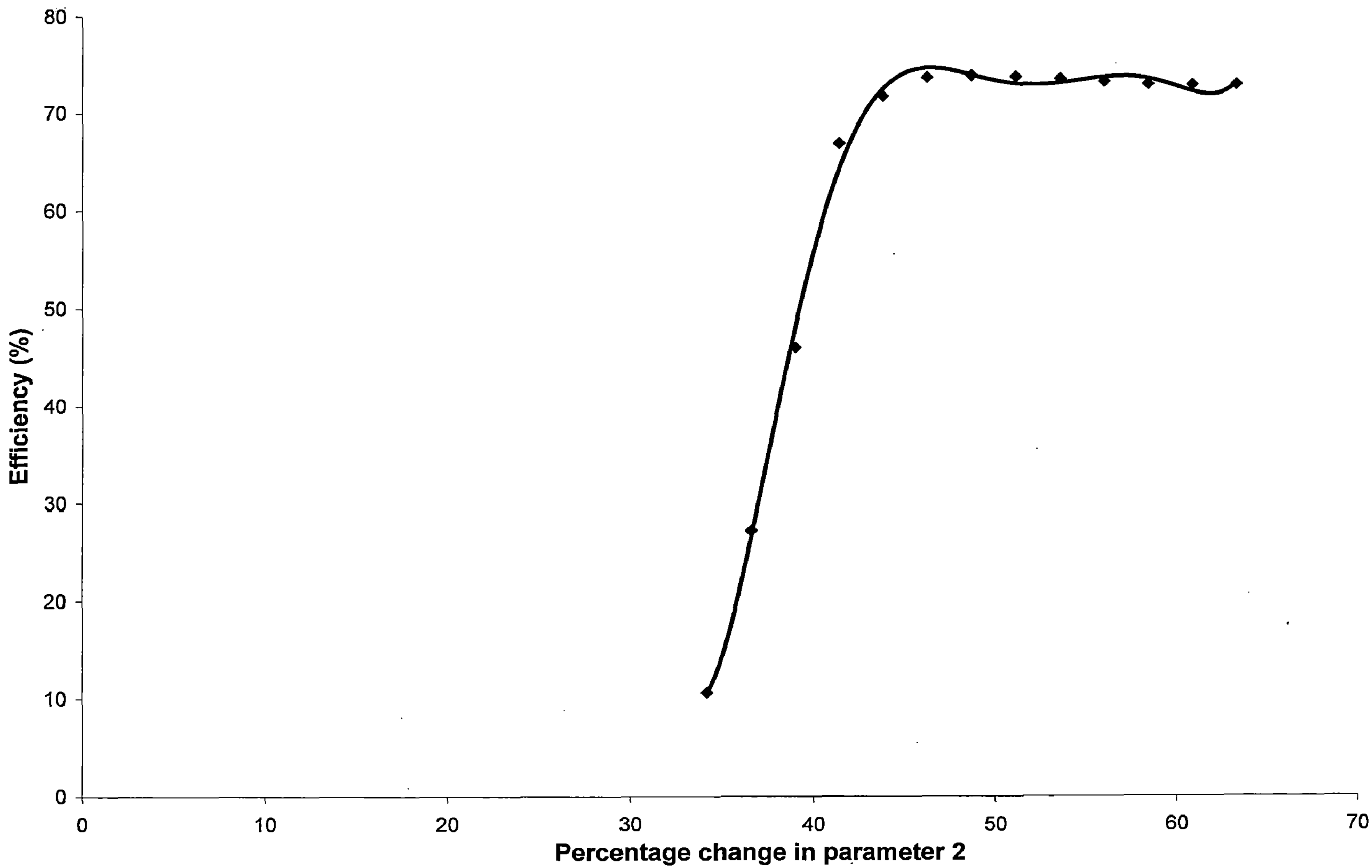

Figure 6.11 Sensitivity of model parameter F_c

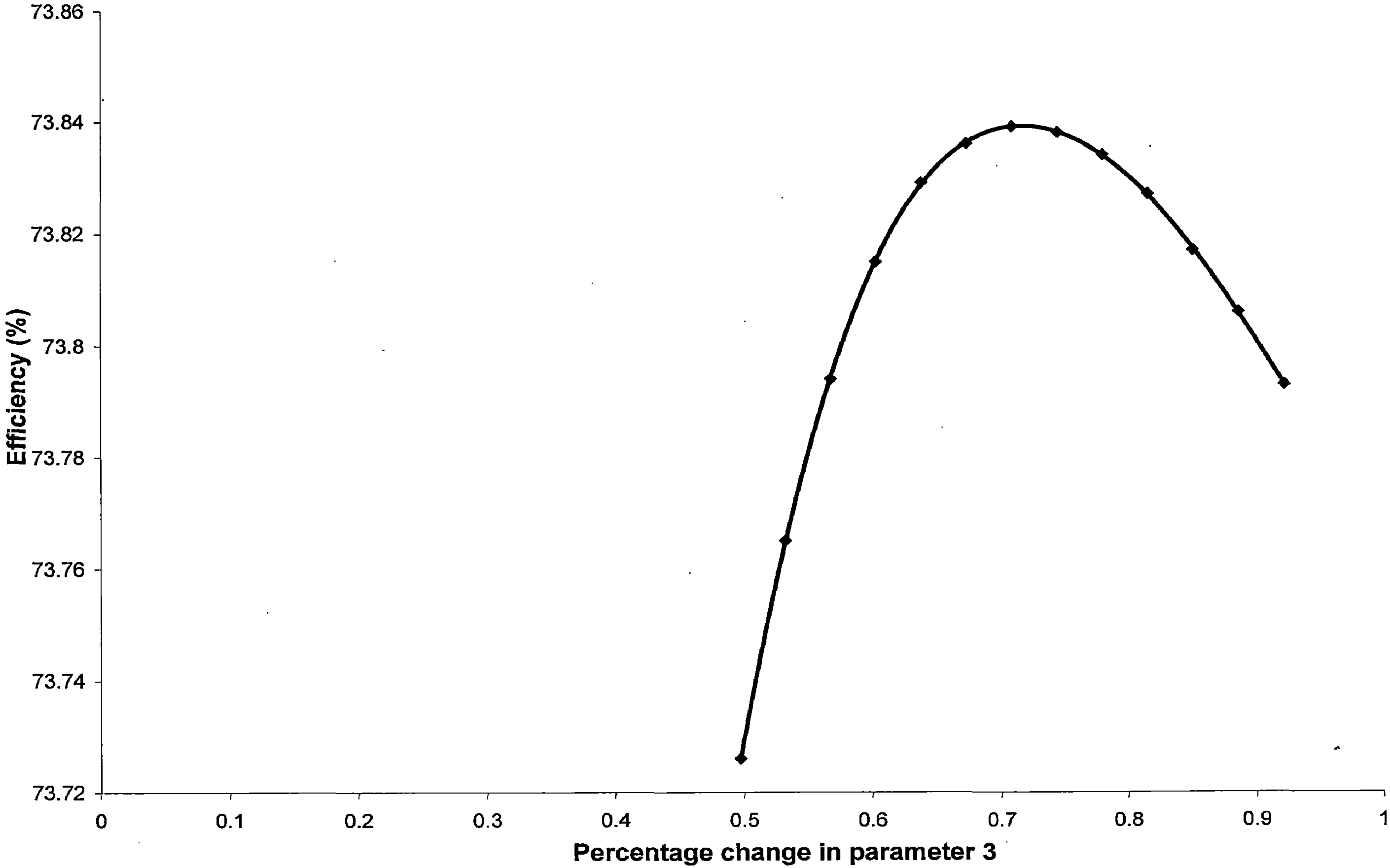

Figure 6.12 Sensitivity of model parameter K

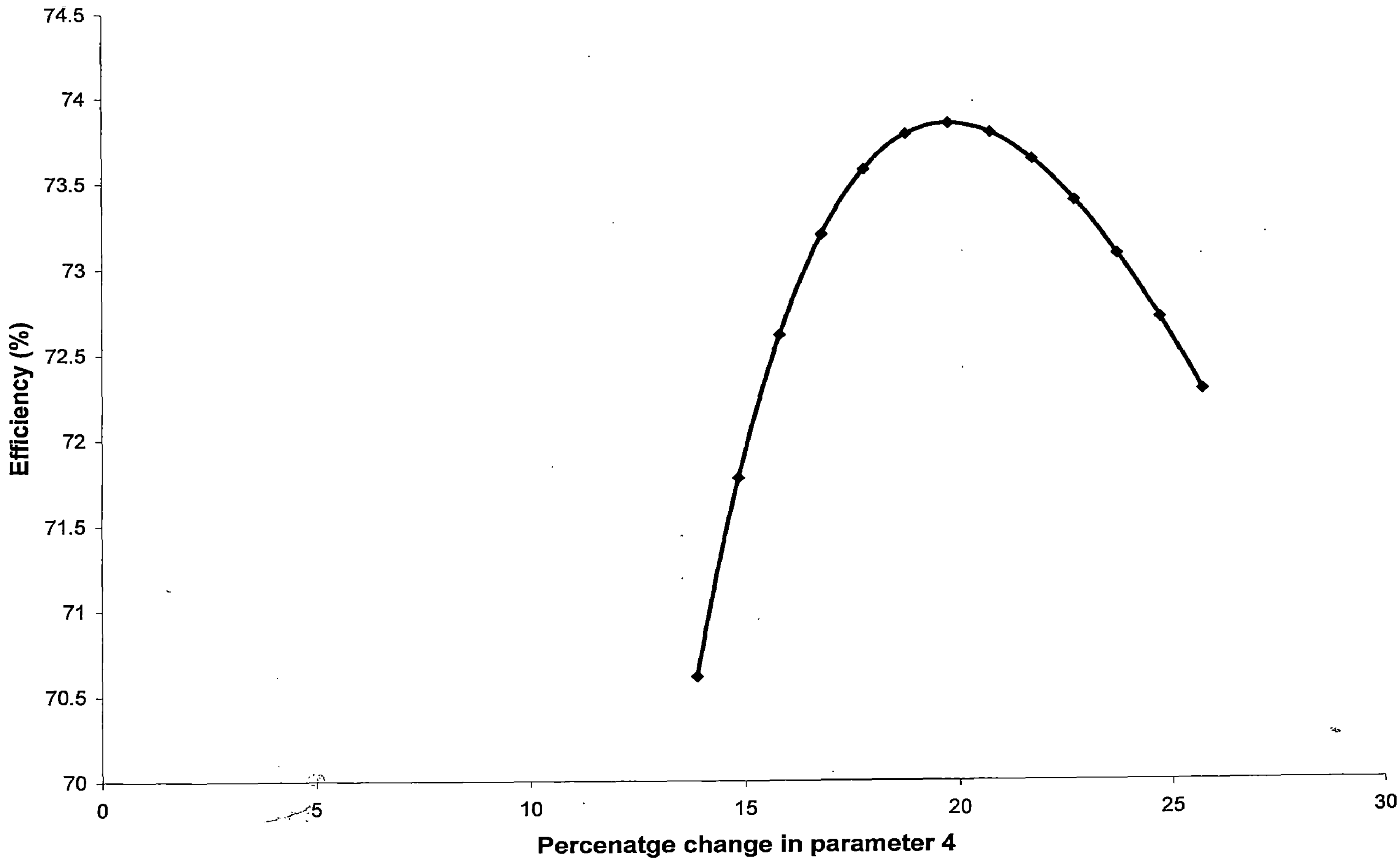

Figure 6.13 Sensitivity of model parameter K_b

CHAPTER 7

SUMMARY AND CONCLUSIONS

The long–term hydrologic simulation plays an important role in water resources planning and watershed management, specifically for analysis of water availability; computation of daily, fortnightly, and monthly flows for reservoir operation; and drought analyses. Since the rainfall data are generally available for a much longer period than are the stream flow data, long – term hydrologic simulation helps extend the gauged data required for the above field applications. In this dissertation, a Soil Conservation Conservation Service Curve Number (SCS-CN)-based long term hydrologic simulation model (Chapter 4) was developed, and tested using the data of a watershed (area = 2785 sq. km) of Satluj river basin. The proposed model has four model parameters, S_0 [L], F_c [L], K [T] and K_b [T]. The first parameter as such represents (in mm) the initial value of the potential maximum retention, F_c represents the infiltration rate (mm/day), K is the catchment storage coefficient (day), and K_b is the ground water storage coefficient (day).

For testing of the above SCS-CN based model, the daily rainfall, runoff and evaporation data of 9 years (1988-97) were used. The first five years data was used for model calibration, and the remaining for validation. The following conclusions can be derived from the study:

(1) The model generally performed poorly as the length of data increased from 1 to 5 years. In yearly simulations, the resulting efficiencies for all the years vary in the range of 70.64 to 94.35%. These values of efficiency however show a satisfactory fit and model performance.

(2) In calibration with the first five years of data, the resulting efficiency was 73.84% and in validation on the remaining fours years of data, it was 72.20%, indicating a satisfactory model performance in both calibration and validation.

(3) The volumetric analysis indicated the segregated components of the various components of hydrologic cycle, such as precipitation, infiltration, initial abstraction, evapotranspiration, baseflow, and total runoff. The model simulated

the yearly runoff values with relative errors in the range (-0.05, 0.74%). These significantly low values indicate a satisfactory model performance. Here, *it* is noted that the yearly runoff was not taken as a constraint in parameter optimization, further supporting the model dependability.

(4) The most significant parameter S_o of the SCS-CN model was less sensitive to variation than other three model parameters, indicating its amenability to field applications employing the NEH-4 CN values or the CN values derived using remote sensing data. In the order of parameters sensitivity, these rank as: $S_o < K_b < K < F_c$.

(5) The satisfactory model performance is further appreciable in view of the limited number of model parameters (only four), simplicity, and no constraints imposed for matching the observed annual runoff volumes.

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APPENDIX I

Program for daily rainfall-runoff modeling using modified SCS-CN method

```
$DEBUG
$LARGE
C     PROGRAM FOR DAILY RAINFALL-RUNOFF MODELLING
C     THIS PROGRAM USES THE MODIFIED SCS-CN METHOD
INCORPORATING 'M' AND 'FC'
C       USES single linear reservoir routing
C       PARAMETER 'S' IS MODIFIED BY EVAPOTRANSPIRATION
C       CHARACTER*80 TITLE
        DIMENSION B(10),Y(1826),BV(10),BMIN(10),BMAX(10),P(12000)
        DIMENSION A(10,10),AC(10,10)
        DIMENSION DIS(365),RF(365),EV(365),DISCHARG(1825)
        DIMENSION EVAPO(1825),F(1825),PANC(1826)
        DIMENSION QCOMP(1825),S(1826),AM(1826),BF(1826),EVATRA(1825)
        DIMENSION AAM(1826),PANC1(365)
        DIMENSION RR(365),QQ(365),QQC(365),FF(365),SS(365)
        DIMENSION BBF(365),EEVTRA(365),QQCOMP(365)
C       DIMENSION NYEAR(10)
        DIMENSION X(1825),Z(1825)
        COMMON /A/ X
        COMMON /B/ S,AM,QCOMP,EVAPO,EVATRA,F,BF,PANC
        COMMON /C/ NYR
        EXTERNAL FUNC,DERIV
        OPEN(UNIT=1,FILE='simulation7.TXT',STATUS='UNKNOWN')
        OPEN(UNIT=3,FILE='SCS.DAT',STATUS='UNKNOWN')
        OPEN(UNIT=4,FILE='test1.OUT',STATUS='UNKNOWN')
C
        READ(1,1293) TITLE
        WRITE(*,*) TITLE
        READ(1,1293) TITLE
        WRITE(*,*) TITLE
        READ(1,1293) TITLE
        WRITE(*,*) TITLE
1293    FORMAT(80A)
C
        READ(1,*) NYR
        WRITE(*,*) NYR
        K=0
        SUMQ=0.0
        SUMRF=0.0
        SUMEVA=0.0
        DO I=1,NYR
```

```
      DO J=1,365
      K=K+1
      READ(1,*) NNN, DIS(J), RF(J), EV(J)
C
      DISCHARG(K)= DIS(J)
      EVAPO(K)=EV(J)
      Y(K)=DISCHARG(K)
      X(K)=RF(J)
      SUMQ=SUMQ+DISCHARG(K)
      SUMRF=SUMRF+X(K)
      SUMEVA=SUMEVA+EVAPO(K)
      ENDDO
      ENDDO
C
      NN=NYR*365
      AMQ=SUMQ/FLOAT(NN)
C
      WRITE(4,4444)SUMQ,SUMRF,SUMEVA
4444  FORMAT(1X,'SUMQ= ',F12.2,2X,'SUMRF= ',F12.2,2X,
      1'SUMEVA= ',F12.2/)
C
C     READ IN INITIAL GUESSES.
C     READ(3,*)SS0,FC,AK,AKBF
      READ (3,*) KK
      READ(3,*) (B(J),J=1,KK)
C     OPTION FOR CALIBRATION AND VALIDATION
      READ(3,*) NOPT
      IF(NOPT.EQ.2) GO TO 300
C
C     READ IN LIMIT ON VARIABLE.
      READ(3,*) (BMIN(J),J=1,KK)
      READ(3,*) (BMAX(J),J=1,KK)
C
      FNU=0.
      FLA=0.
      TAU=0.
      EPS=0.
      PHMIN=0.
      I=0
      KD=KK
      DO 100 J=1,KK
      BV(J)=1
100   CONTINUE
      ICON=KK
      ITER=0
      NO=6
```

```
      WRITE(NO,1511)
1511  FORMAT(1H1,10X,27HBSOLVE REGRESSION ALGORITHM )
C
      PH2=0.0
200   CALL BSOLVE(KK,B,NN,Z,Y,PH,FNU,FLA,TAU,EPS,PHMIN,I,ICON,BV
     1,BMIN,BMAX,P,FUNC,DERIV,KD,A,AC,GAMM)
C
      ITER=ITER+1
      PH1=PH
      WRITE(NO,001) ICON,PH,ITER
      IF(ABS((PH1-PH2)/PH1).LE.0.00001)GO TO 300
      PH2=PH1
      IF(PH.LE.0.000001)GO TO 300
001   FORMAT(/,2X,'ICON = ',I3,4X,5HPH = ,E15.8,4X'ITERATION
     1 NO. =',I3)
      IF(ICON) 10,300,200
10    IF(ICON+1) 20,60,200
20    IF(ICON+2) 30,70,200
30    IF(ICON+3) 40,80,200
40    IF(ICON+4) 50,90,200
50    GO TO 95
60    WRITE(NO,004)
004   FORMAT(//,2X,32HNO FUNCTION IMPROVEMENT POSSIBLE )
      GOTO 300
70    WRITE(NO,005)
005   FORMAT(//,2X,28HMORE UNKNOWNS THAN FUNCTIONS)
      GOTO 300
80    WRITE(NO,006)
006   FORMAT(//,2X,24HTOTAL VARIABLES ARE ZERO)
      GOTO 300
90    WRITE(NO,007)
007   FORMAT(//,2X,'HCORRECTIONS SATISFY CONVERGENCE
REQUIREMENTS',
     1' BUT LAMDA FACTOR (FLA) STILL LARGE')
      GOTO 300
95    WRITE(NO,008)
008   FORMAT(//,2X,20HTHIS IS NOT POSSIBLE)
      GOTO 300
300   WRITE(4,002)
002   FORMAT(//,2X,24HSOLUTION OF THE EQUATION)
      DO 400 J=1,KK
      WRITE(4,003) J,B(J)
      WRITE(*,003) J,B(J)
003   FORMAT(/,2X,2HB(,I2,4H)= ,E16.8)
400   CONTINUE
      CALL FUNC(KK,B,NN,Z)
```

```
C
      WRITE(4,11)
11    FORMAT(1X,' DAY  RAINFALL     S  RF-EXCESS   INFILT ',
     1'BASEFLOW RUNOFF(C) RUNOFF(O)  EVAPTRA    AMOIST     PANC'/)
      SUMFO=0.0
      SUMF1=0.0
      K=0
      DO I=1,NYR
      K1=0
      DO J=1,365
      K=K+1
      K1=K1+1
      SUMFO=SUMFO+(DISCHARG(K)-AMQ)**2
      SUMF1=SUMF1+(DISCHARG(K)-Z(K))**2
      RR(K1)=X(K)
      FF(K1)=F(K)
      AAM(K1)=AM(K)
      PANC1(K1)=PANC(K)
      QQ(K1)=DISCHARG(K)
      QQC(K1)=Z(K)
      SS(K1)=S(K)
      BBF(K1)=BF(K)
      EEVTRA(K1)=EVATRA(K)
      QQCOMP(K1)=QCOMP(K)
      WRITE(4,1294) K1,RR(K1),SS(K1),QQCOMP(K1),FF(K1),
     1 BBF(K1),QQC(K1),QQ(K1),EEVTRA(K1),AAM(K1),PANC1(K1)
1294  FORMAT(1X,I5,1X,10F10.2)
      ENDDO
      ENDDO
      EFF=(1-SUMF1/SUMFO)*100.
      WRITE(4,1295)EFF
      WRITE(*,1295)EFF
1295  FORMAT(1X,'EFFICIENCY= ',1X,F10.3)
      STOP
      END
C
      SUBROUTINE LEAP(NYEAR,ND)
      IF(AMOD(FLOAT(NYEAR),4.).EQ.0.)THEN
      ND=29
      ELSE
      ND=28
      ENDIF
      RETURN
      END
C************************************************************
C   THIS IS SUBROUTIUNE FOR FUNCTION
```

```
      SUBROUTINE FUNC (KK,B,NN,Z)
C
    DIMENSION F(1825),BF(1826),QCOMP(1825),EVAPO(1825)
      DIMENSION X(1825),Z(1825),QC(1826),B(10)
      DIMENSION SS(1826),EVATRA(1825),AM(1826),PANC(1826)
      COMMON /A/ X
      COMMON /B/ SS,AM,QCOMP,EVAPO,EVATRA,F,BF,PANC
      COMMON /C/ NYR
C HERE, X IS RAINFALL, Z IS THE COMPUTED OUTFLOW (mm)
C AM IS THE ANTECEDENT MOISTURE
C FD IS THE DYNAMIC INFILTRATION
C DEFINE HERE THE WHICH B() PARAMETER REFERS TO WHICH REAL
PARAMETER.
      SS0 = B(1)
      FC = B(2)
      AK = B(3)
      AKBF=B(4)
C COMPUTATION OF COURANT NUMBER AND C0, C1, AND C2
      COUR=1./AK
      C0=COUR/(2.+COUR)
      C1=C0
      C2=(2.-COUR)/(2.+COUR)
C
      COUR1=1./AKBF
      D0=COUR1/(2.+COUR1)
      D1=D0
      D2=(2.-COUR1)/(2.+COUR1)
C     COMPUTATIONS BEGIN
      K=0
     SS(1)=SS0
      AM(1)=0.0
      QC(1)=0.0
      BF(1)=0.0
      AL=0.25
     DO 2 I=1,NYR
     DO 3 J=1,365
      K=K+1
      PEF=X(K)-AL*SS(K)
            IF(PEF.LE.0.0)THEN
            FCC=0.0
            FD = 0.0
            QCOMP(K)=0.0
            ELSEIF(PEF.LE.FC)THEN
            FCC= PEF
            QCOMP(K)=0.0
            FD = 0.0
```

```
          ELSE
     QCOMP(K)=(PEF-FC)*(PEF-FC+AM(K))/(PEF-FC+AM(K)+SS(K))
          FD= PEF-FC-QCOMP(K)
          IF(FD.LE.0.0)FD=0.0
          FCC=FC
          ENDIF
      F(K)=FD+FCC
      AM(K+1)=FD
      PANC(K)= SS(K)/SS0
      EVATRA(K)=(1-PANC(K)*PANC(K))*EVAPO(K)
      SS(K+1)=SS(K)-AM(K)+EVATRA(K)
      IF(SS(K+1).LE.0.0)SS(K+1)=0.001
      IF(SS(K+1).GE.SS0)SS(K+1)=SS0
      AL=PANC(K)
C
C     ROUTING OF COMPUTED OUTFLOW
      QC(K+1)=C0*QCOMP(K)+C1*QCOMP(K)+C2*QC(K)
C     BASEFLOW ROUTING
      BF(K+1)=D0*FCC+D1*FCC+D2*BF(K)
      IF(BF(K+1).LE.0.0)BF(K+1)=0.0
C     TOTAL RUNOFF
      Z(K)=QC(K)+BF(K)
3     CONTINUE
2     CONTINUE
      RETURN
      END
C**********************************************************************
      SUBROUTINE BSOLVE(KK,B,NN,Z,Y,PH,FNU,FLA,TAU,EPS,PHMIN,I,ICON,
     1BV,BMIN,BMAX,P,FUNC,DERIV,KD,A,AC,GAMM)
      DIMENSION B(10),Z(1825),Y(1826),BV(10),BMIN(10),BMAX(10)
      DIMENSION P(12000)
      DIMENSION A(10,10),AC(10,10),X(1825)
      COMMON /A/ X
      K=KK
      N=NN
      KP1=K+1
      KP2=KP1+1
      KBI1=K*N
      KBI2=KBI1+K
      KZI=KBI2+K
      IF(FNU.LE.0.) FNU=10.0
      IF(FLA.LE.0.) FLA=0.01
      IF(TAU.LE.0.) TAU=0.001
      IF( EPS.LE.0.) EPS=0.00002
      IF(PHMIN.LE.0.) PHMIN=0.0
120   KE=0
```

```
130   DO 160 I1=1,K
160   IF(BV(I1).NE.0.0) KE=KE+1
       IF(KE.GT.0) GOTO 170
162   ICON=-3
163   GOTO 2120
170   IF(N.GE.KE) GOTO 500
180   ICON=-2
190   GOTO 2120
500   I1=1
530   IF(I.GT.0) GOTO 1530
550   DO 560 J1=1,K
       J2=KBI1+J1
       P(J2)=B(J1)
       J3=KBI2+J1
560   P(J3)=ABS(B(J1))+1.0E-02
       GOTO 1030
590   IF(PHMIN.GT.PH.AND.I.GT.1) GOTO 625
       DO 620 J1=1,K
       N1=(J1-1)*N
       IF(BV(J1)) 601,620,605
601   CALL DERIV(K,B,N,Z,P(N1+1),J1,JTEST)
       IF(JTEST.NE.(-1)) GOTO 620
       BV(J1)=1
605   DO 606 J2=1,K
       J3=KBI1+J2

606   P(J3)=B(J2)
       J3=KBI1+J1
       J4=KBI2+J1
       DEN=0.001*AMAX1(P(J4),ABS(P(J3)))
       IF(P(J3)+DEN.LE.BMAX(J1)) GOTO 55
       P(J3)=P(J3)-DEN
       DEN=-DEN
       GOTO 56
55    P(J3)=P(J3)+DEN
56    CALL FUNC(K,P(KBI1+1),N,P(N1+1))
       DO 610 J2=1,N
       JB=J2+N1
610   P(JB)=(P(JB)-Z(J2))/DEN
620   CONTINUE
625   DO 725 J1=1,K
       N1=(J1-1)*N
       A(J1,KP1)=0.
       IF(BV(J1)) 630,692,630
630   DO 640 J2=1,N
       N2=N1+J2
```

```
640   A(J1,KP1)=A(J1,KP1)+P(N2)*(Y(J2)-Z(J2))
650   DO 680 J2=1,K
660   A(J1,J2)=0.0
665   N2=(J2-1)*N
670   DO 680 J3=1,N
672   N3=N1+J3
674   N4=N2+J3
680   A(J1,J2)=A(J1,J2)+P(N3)*P(N4)
       IF(A(J1,J1).GT.1.E-20) GOTO 725
692   DO 694 J2=1,KP1
694   A(J1,J2)=0.0
695   A(J1,J1)=1.0
725   CONTINUE
       GN=0.
       DO 729 J1=1,K
729   GN=GN+A(J1,KP1)**2
       DO 726 J1=1,K
726   A(J1,KP2)=SQRT(A(J1,J1))
       DO 727 J1=1,K
       A(J1,KP1)=A(J1,KP1)/A(J1,KP2)
       DO 727 J2=1,K
727   A(J1,J2)=A(J1,J2)/(A(J1,KP2)*A(J2,KP2))
730   FL=FLA/FNU
       GOTO 810
800   FL=FNU*FL
810   DO 840 J1=1,K
820   DO 830 J2=1,KP1
830   AC(J1,J2)=A(J1,J2)
840   AC(J1,J1)=AC(J1,J1)+FL
       DO 930 L1=1,K
       L2=L1+1
       DO 910 L3=L2,KP1
910   AC(L1,L3)=AC(L1,L3)/AC(L1,L1)
       DO 930 L3=1,K
       IF(L1-L3) 920,930,920
920   DO 925 L4=L2,KP1
925   AC(L3,L4)=AC(L3,L4)-AC(L1,L4)*AC(L3,L1)
930   CONTINUE
       DN=0.
       DG=0.
       DO 1028 J1=1,K
       AC(J1,KP2)=AC(J1,KP1)/A(J1,KP2)
       J2=KBI1+J1
       P(J2)=AMAX1(BMIN(J1),AMIN1(BMAX(J1),B(J1)+AC(J1,KP2)))
       DG=DG+AC(J1,KP2)*A(J1,KP1)*A(J1,KP2)
       DN=DN+AC(J1,KP2)*AC(J1,KP2)
```

```
1028  AC(J1,KP2)=P(J2)-B(J1)
      COSG=DG/SQRT(DN*GN)
      JGAM=0
      IF(COSG) 1100,1110,1110
1100  JGAM=2
      COSG=-COSG
1110  CONTINUE
      COSG=AMIN1(COSG,1.0)
      GAMM=ARCOS(COSG)*180./(3.14159265)
      IF(JGAM.GT.0)GAMM=180.-GAMM
1030  CALL FUNC(K,P(KBI1+1),N,P(KZI+1))
1500  PHI=0.
      DO 1520 J1=1,N
      J2=KZI+J1
1520  PHI=PHI+(P(J2)-Y(J1))**2
      IF(PHI.LT.1.E-10) GOTO 3000
      IF(I.GT.0) GOTO 1540
1521  ICON=K
      GOTO 2110
1540  IF(PHI.GE.PH) GOTO 1530
C
C  EPSILON TEST
C
1200  ICON=0
      DO 1220 J1=1,K
      J2=KBI1+J1
1220  IF(ABS(AC(J1,KP2))/(TAU+ABS(P(J2))).GT.EPS) ICON=ICON+1
      IF(ICON.EQ.0) GOTO 1400
C
C  GAMMA LAMDA TEST
C
      IF (FL.GT.1.0.AND.GAMM.GT.90.0) ICON=-1
      GOTO 2105
C
C  GAMMA EPSILON TEST
C
1400  IF(FL.GT.1.0.AND.GAMM.LE.45.0) ICON=-4
      GOTO 2105
C
C
1530  IF(I1-2) 1531,1531,2310
1531  I1=I1+1
      GOTO (530,590,800),I1
2310  IF(FL.LT.1.0E+8) GOTO 800
1320  ICON=-1
C
```

```
2105  FLA=FL
      DO 2091 J2=1,K
      J3=KBI1+J2
2091  B(J2)=P(J3)
2110  DO 2050 J2=1,N
      J3=KZI+J2
2050  Z(J2)=P(J3)
      PH=PHI
      I=I+1
2120  RETURN
3000  ICON=0
      GOTO 2105
C
      END
C
      FUNCTION ARCOS(Z)
C
      X=Z
      KEY=0
      IF(X.LT.(-1.)) X=-1.
      IF(X.GT.1.) X=1.
      IF(X.GE.(-1.) .AND.X.LT.0.) KEY=1
      IF(X.LT.0.)  X=ABS(X)
      IF(X.EQ.0.)  GO TO 10
      ARCOS=ATAN(SQRT(1.-X*X)/X)
      IF(KEY.EQ.1) ARCOS=3.14159265-ARCOS
      GOTO 999
10    ARCOS=1.5707963
C
999   RETURN
      END
C*************************************************************
      SUBROUTINE DERIV(K,B,N,Z,P,J1,JTEST)
      RETURN
      END
```