STORM RUNOFF FORECASTING MODEL
INCORPORATING SPATIAL DATA

by

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SIGNED: [Signature]
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Abstract

This study is concerned with design forecasting of storm hydrographs with emphasis on runoff volume and peak discharge. The objective of the study was to develop, calibrate and test a method for forecasting storm runoff from small semi-arid watersheds using an available prediction model.

In order to turn the selected prediction model into a forecasting model an objective procedure in terms of an API-type model was developed for evaluating the soil moisture deficit in the upper soil layer at the beginning of each storm.

Distinction was made between the physically-based parameters and the other fitting parameters. The rainfall excess calculation was computed by solving the Green and Ampt equation for unsteady rainfall conditions using the physically-based parameters.

For the physically-based parameters a geographic information system was developed in order to account for the variability in time and space of the input data and the watershed characteristics and to coregister parameters on a common basis.

The fitting parameters were used to calibrate the model on one subwatershed in the Walnut Gulch Experimental Watershed while the physically-based parameters remained constant. Two objective functions were selected for the optimization procedure. These functions expressed the goodness of
fit between the calculated hydrograph volume and peak discharge and the observed volume and peak discharge.

Linear relationships between the effective matric potential parameter and the two objective functions obtained from the sensitivity analyses made it possible to develop a bilinear interpolation algorithm to minimize, simultaneously, the difference between the calculated and observed volume and peak discharge.

The prediction mode of the model was tested both on different storm events on the same subwatershed and on another subwatershed with satisfactory results. In the prediction mode the effective matric potential parameter was allowed to vary from storm to storm, however, in the forecasting mode these values were obtained from the API model. Relatively poor results were obtained in testing the forecasting mode on another subwatershed. These errors were able to be corrected by changing the channel losses fitting parameters.
Chapter 1

INTRODUCTION

Many mathematical rainfall–runoff models are employed today by hydrologists and engineers for a wide variety of uses. These models are used to manipulate and analyze data representing physical and biological parameters that influence precipitation distribution, water runoff and numerous other related factors. These models can be “predictive” which is the long-term statistical hydrograph simulation for engineering design or “forecasting” which is the short-term process such as the estimation of a specific future event (Clarke, 1973). Clarke (1973) further differentiates between design forecasting and operational forecasting. In design forecasting hypothetical watershed conditions, such as soil moisture and rainfall, are used for estimation of the resultant runoff hydrograph. Operational forecasting refers to real-time conditions when one is given the sequence of flow rates at a site and perhaps also the percent flow rates upstream, and asked to estimate future flows. Freeze (1982) called design forecasting “one-step-ahead prediction”.

Runoff forecasting is perhaps the most difficult problem encountered by hydrologists. Forecasting of runoff is required for many aspects of planning,
design and management of water resources and other engineering systems. Schultz (1986) summarizes the various purposes of flow forecasting and their relative importance:

1. Flood protection (43%).
2. Energy (19%).
3. Navigation (12%).
4. Water supply and salination (12%).
5. Irrigation (6%).
6. Water pollution control (4%).
7. Ice problem (4%).

The elements to be forecast are:

1. Surface water level (42%).
2. Discharge (36%).
3. Volume of runoff (21%).
4. Ice, groundwater, water quality (seldom).

This research is chiefly concerned with design forecasting of storm hydrographs with emphasis on the runoff volume and the peak discharge. For the model to be easily applied to various areas and data forms, the model must be designed to receive as input those data which are available for most watersheds. Traditional data sources are rain gage stations and soil surveys. More modern and sophisticated data sources include remote sensing
CHAPTER 1. INTRODUCTION

devices such as weather radar and satellite imagery. Because both types of data sources have spatial variability, a distributed model is preferred over a lumped model as will be discussed in Chapter 2.

The geographic information system is a helpful tool in a distributed model. The development of a distributed model geographic information system (Chapter 6) makes it possible to account for the variabilities in time and space of the input and the watershed characteristics and to coregister variables and parameters one to another on a common base.

Two basic steps are required for developing a forecasting model. The first step is developing a prediction model which is concerned mainly with the hydrograph simulation, including the computation of rainfall excess, conversion of rainfall excess to surface outflow, routing the channel inflow and subtracting the channel losses. The second step is the addition of an objective procedure for evaluating the soil moisture deficit at the beginning of each storm event to the prediction model. The initial moisture value prior to a selected event is usually a significant parameter in the forecasting model (Main and Larson, 1971; Skaggs and Khaleel, 1982).

The objective of this study is to develop, calibrate and test a method for forecasting storm runoff from semi-arid watersheds using an available prediction rainfall-runoff model. The prediction version of CELLMOD (Diskin and Simpson, 1978; Diskin et al., 1984) was selected among other existing models because of its unique structure. The model divides watersheds into subwatersheds or interconnected cell units which represent about the same size area as the data received from field survey or remote sensing devices. The prediction model was modified here into a forecasting model.

The forecasting version of CELLMOD can be defined as a parametric, semi-distributed, quasi-linear, design forecasting model. An advantage of
CHAPTER 1. INTRODUCTION

the modified model is that input data to the model can be determined by remote sensing techniques used to monitor and inventory natural resources.

The theoretical background of the model is described in Chapter 2 including definitions of various related models such as physically based vs. parametric models, distributed vs. lumped models and linear vs. non-linear models. Chapter 3 presents the general outline of the model. Chapter 4 concentrates on modification of the CELLMOD model to permit use of the Green and Ampt model for calculating rainfall excess under unsteady rainfall conditions. Chapter 5 describes development of an API-type model to provide the initial soil moisture deficit prior to a selected event. This is a significant parameter that converts the prediction model into a forecasting model. The geographic information system developed in Chapter 6 extends application of the model to a range of watershed conditions.

The model operation demonstrated in Chapter 7 contains the required input data, internal data manipulation and processing and the model outputs are demonstrated for one rainfall-runoff event. Chapter 8 presents the model evaluation procedure including calibration, sensitivity analysis, and optimization, as well as tests of the model on different storm events and different watersheds. A summary and conclusions are presented in Chapter 9.
Chapter 2

THEORETICAL BACKGROUND FOR CELLMOD

2.1 Introduction

Before describing CELLMOD, the rainfall-runoff model on which the present study is based, it is necessary to introduce a few related model definitions. This chapter will describe the differences between physically-based and parametric models, between distributed and lumped models and between linear and non-linear models. In addition, this chapter will introduce the derivation and the theoretical background of the main routines of the model.

2.2 Model classification

2.2.1 Physically-based vs. parametric models

In rainfall-runoff modeling it is common to differentiate between physically-based and parametric models. The former type of models attempt to simu-
CHAPTER 2. THEORETICAL BACKGROUND FOR CELLMOD

late the rainfall–runoff event by certain physical laws (such as the conservation of mass). The parametric models simulate the same type of events by approximating the physical laws governing the various components of the rainfall–runoff system (such as infiltration, routing, and soil moisture storage) by a set of equations which give the best fitting output (Dawdy et al., 1972).

The physically–based models are believed to be more representative of the real system, and to produce more accurate results. They can be more complicated requiring relatively large computer facilities and data bases. Physically–based models which are suited for use in ungaged watersheds may not require calibration data, but do require a large amount of observed field data and knowledge of the basin characteristics. These factors tend to make them more expensive to operate. Conversely, parametric models are relatively simple to compute and to use. Parametric models require a large amount of data for calibration but, once calibrated, can be used efficiently and inexpensively.

The model used in this study is essentially a parametric model which simulates the physical conditions by a deterministic mathematical description. However, by applying physically–based procedures and using measurable parameters the model appropriates the physical laws governing rainfall–runoff hydrology.

2.2.2 Distributed vs. lumped models

Distinction should be made between distributed and lumped models. According to Clarke (1973, p. 5) a lumped model “takes no account of the spatial distribution in the input variable, nor of the spatial variability in parameters characterizing the physical process acting upon input”. Conse-
The attractive features of lumped models are that they are simpler, less expensive and require a relatively small number of parameters. However, the results from lumped models are often less accurate than those of distributed models. Furthermore, Diskin and Simpson (1978) comment that some of the nonlinearity observed in surface runoff systems is due to the lumped input assumption.

Distributed models are much more complicated than lumped models and thus have an added price in terms of model complexity, input data requirements and operation (computer) costs (Larson et al., 1982). Field and input data for a fully distributed model are rarely available, especially on ungaged watersheds. On the other hand, these models have better potential for more accurate simulation of the runoff process if they are well designed and operated (Huggins et al., 1977).

A semi-distributed model represents an intermediate approach that falls between these two extremes (Diskin and Simpson, 1978; Knudsen et al., 1986). In this type of model the watershed area is subdivided into a number of elements (grid system or cells), each of which receives a different rainfall input value and has different values of other parameters or variables. The runoff is first calculated separately for each element and then routed through the system.

A semi-distributed model consisting of a series of cascading reservoirs, termed model cells, was selected for study because of its ability to take advantage of features of both the lumped and the distributed models and
also because of its ability to work in connection with remotely sensed data. Remote sensing provides data in grid formats such as weather radar pixels for rainfall input or satellite images for canopy cover or soil moisture data.

2.2.3 Linear vs. non-linear models

The definition of linearity will be discussed in detail later in the chapter. For the moment, it suffices to state that a linear model is one which satisfies two conditions—homogeneity and superposition. In addition, a model is said to be linear time-invariant if the parameters do not change with time. If any of the parameters are allowed to vary between storm events, a quasi-linear model is obtained which accounts for some nonlinearities of the process being modeled.

Empirically it was found that a linear model usually introduces bias into the model output. In the current study the model accounts for nonlinearities in the watershed response by accommodating varying soil moisture deficit values, which are a key variable in the hydrological model.

Therefore, the model used in this study is defined as quasi-linear.

2.3 Linear systems

2.3.1 Definition of linearity

According to Dooge (1973 p. 4), a system is defined as "Any structure, device, scheme, or procedure, real or abstract, that interrelates in a given time reference, an input, cause, or stimulus, of matter, energy, or information, and an output, effect, or response of information, energy or matter." This most general definition includes three parts which every system dealing with time as a variable contains: input with respect to time, \( X(t) \), opera-
tor, Φ, and output with respect to time, Y(t). A system can be illustrated schematically as

\[ X(t) \rightarrow \Phi \rightarrow Y(t) \]

In surface hydrology an example of the system input is the rainfall excess, the output is the direct runoff and the operator can be the convolution integral.

A system is said to be linear if it satisfies the following two conditions (here an arrow means that a particular input to the system results in a particular output):

1. Homogeneity:
   if \( X(t) \rightarrow Y(t) \)
   then \( aX(t) \rightarrow aY(t) \)

2. Superposition:
   if \( X_1(t) \rightarrow Y_1(t) \)
   and \( X_2(t) \rightarrow Y_2(t) \)
   then \( X_1(t) + X_2(t) \rightarrow Y_1(t) + Y_2(t) \)

Thus, if a system is linear,

\[ \alpha X_1(t) + \beta X_2(t) \rightarrow \alpha Y_1(t) + \beta Y_2(t) \]

where \( \alpha \) and \( \beta \) are constants.

Let \( \tau \) be the time shift which can be either positive or negative, a system is said to be time-invariant if all its parameters have constant values which do not change with time. Thus,
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if \( X(t) \rightarrow Y(t) \)
then \( X(t + \tau) \rightarrow Y(t + \tau) \)

In a time-invariant system the form of the output depends only on the form of the input and not on the time at which the input is applied.

All unit hydrograph procedures (analytic or synthetic) are based on these fundamental superposition and invariance principles (Dooge, 1959). The hydrograph of surface runoff from a watershed, resulting from a given pattern of rainfall excess (rainfall minus infiltration and other losses) is built by superimposing the hydrographs resulting from rainfall excess during small unit time periods.

1.3.2 Linear reservoir

A linear reservoir is a conceptual hydrological system represented by a reservoir. This system assumes that its output (the runoff rate) with respect to time, \( Q(t) [L/T] \), is linearly related to the storage with respect to time \( S(t) [L] \):

\[
S(t) = KQ(t)
\]  

(1.1)

This is the storage equation in which \( K \) is the proportionality constant \([T]\), also called the storage coefficient or the reservoir constant. \( K \) is equal to the average delay time imposed on an inflow by the reservoir (Dooge, 1959). By the continuity equation it can be shown that

\[
Q(t) - P(t) = \frac{dQ}{dt}
\]  

(1.2)

in which \( P(t) \) is the system input with respect to time or the rainfall excess rate \([L/T]\). Combining the storage equation with the continuity equation
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leads to
\[ Q(t) - P(t) = K \frac{dQ}{dt} \] (1.3)

The solution of Eq. 2.3, considering the initial condition \( Q = 0 \) when \( t = 0 \), is
\[ Q(t) = P(t)(1 - e^{-t/K}) \] (1.4)

When \( t \) approaches infinity, the reservoir's input is equal to its output which means that the outflow approaches an equilibrium condition. Let \( \tau \) be the time since inflow terminated (\( \tau = t - t_0 \)). If the inflow terminates at time \( (t = t_0) \) at which time \( Q = Q_0 \), then with the condition of \( \tau = t - t_0 \) Eq. 2.3 yields
\[ \frac{dQ}{dt} + \frac{Q(t)}{K} = 0 \quad \forall \; t \geq t_0 \] (1.5)

with the solution which expressed the outflow at time \( t \) in terms of discharge \( Q_0 \) at \( t_0 \) as
\[ Q(t) = Q_0 e^{-t/K} \quad \forall \; t = t - t_0 \] (1.6)

In Eq. 2.6 it can be shown that when \( t \) approaches infinity, \( Q(t) \) approaches 0. Thus, Eq. 2.4 describes the rising limb of the hydrograph during rainfall excess and Eq. 2.6 the recession limb when rainfall excess rate is zero and after the peak maximum runoff rate has occurred.

1.3.3 Instantaneous unit hydrograph (IUH)

For an instantaneous inflow which fills the reservoir of storage \( S \) in \( t_0 = 0 \), Eq. 2.1 becomes
\[ Q_0 = \frac{S_0}{K} \] (1.7)
CHAPTER 2. THEORETICAL BACKGROUND FOR CELLMOD

In this case \( \tau = t \) and Eq. 2.6 becomes

\[
Q(t) = P(t) e^{-t/K} = \frac{S_0}{K} e^{-t/K}
\]  

(2.8)

The IUH for a linear reservoir, \( U(t) \), for a unit impulse input or \( S = 1 \), is

\[
U(t) = \frac{1}{K} e^{-t/K}
\]  

(2.9)

Eq. 2.9 is known as the impulse response function which describes the response of a linear reservoir to an impulse input function as a sudden jump at the instant of inflow to a finite outflow followed by an exponential line approaching infinity as illustrated in Fig. 2.1 (Dooge, 1959). Note that the hydrograph described by Eq. 2.9 has no rising limb. The impulse response function is the unknown function in the convolution integral

\[
Q(t) = \int_0^t \frac{1}{K} e^{-\tau/K} P(t - \tau) d\tau
\]  

(2.10)

where \( \tau \) is a dummy variable of integration.

The output of a linear time invariant system, such as a linear reservoir, is given by the convolution of the impulse response of the watershed expressed by the instantaneous unit hydrograph with the impulse input function.

2.3.4 Cascaded reservoirs

Based on the convolution integral, Nash (1957) derived a conceptual watershed model for a series of \( n \) identical linear reservoirs, each having the same hydrologic response and the same storage coefficient, \( K \).

With an impulse input, \( I \), the outflow from the first reservoir (Eq. 2.9) becomes the inflow to the second reservoir (Fig. 2.2), and Eq. 2.10 becomes
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Figure 2.1: Theoretical IUH model for a linear reservoir (after Huggins and Burney, 1982).

Figure 2.2: Nash model of Cascaded reservoir (after Huggins and Burney, 1982).
CHAPTER 2. THEORETICAL BACKGROUND FOR CELLMOD

\[ Q_2(t) = \int_0^t \frac{1}{K} e^{-r/K} \frac{1}{K} e^{-(t-r)/K} dr = \frac{t}{K^2} e^{-t/K} \]  \hspace{1cm} (2.11)

which is the output from the second reservoir. The output from the \( n \)-th reservoir will be

\[ Q_n(t) = U(t) = \frac{1}{K(n-1)!} (t/K)^{n-1} e^{-t/K} \]  \hspace{1cm} (2.12)

as the IUH of a cascade of \( n \) identical linear reservoirs.

The Nash model is linear since the storage coefficient \( K \) is constant, however, the model can be quasi-linear if \( K \) is made a variable of \( Q \) as will be shown later.

2.3.5 Linear channel

A linear channel is analogous to the concept of a linear reservoir whose storage outflow curve is a straight line. A linear channel is a fictitious channel defined as a reach in which the rating curve at every point is in linear relationship between discharge and area (Dooge, 1959). Consequently, when the inflow hydrograph is routed through the linear channel its shape remains unchanged. However it does shift (translate) in time, as illustrated in Fig. 2.3a. At a given channel cross section, the relation between the cross sectional area \( A \) \([L^2]\) and the discharge \( Q \) \([L^3/T]\) is linear

\[ A = C \cdot Q \]  \hspace{1cm} (2.13)

where \( C \) \([T]\) is a function of the translation time called the translation coefficient and is constant for a given cross section.

If a segment of inflow of duration increment \( DT \) and volume \( V \) is routed through a linear channel (Fig. 2.3b) the outflow is
Figure 2.3: Theoretical linear channel model: (a) inflow and outflow translation; (b) routing a segment hydrograph through a linear channel; (c) IUH ((a) and (c) after Huggins and Burney, 1982; (b) after Chow, 1964).
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\[ Q = V \cdot \delta(t, DT) \]  \hspace{1cm} (2.14)

where:

\[ \delta(t, DT) = \begin{cases} 
\frac{1}{DT} & \text{for } 0 \leq \tau \leq DT \text{ and } t = \tau + T \\
0 & \text{elsewhere} 
\end{cases} \]  \hspace{1cm} (2.15)

Eq. 2.15 is a pulse function where \( \tau \) is the time shift measured from the beginning of the segment and \( T \) is the channel travel time. When \( DT \) approaches zero, this function becomes an impulse function \( \delta(t) \), known as the \textit{Dirac-Delta function}, which represents the IUH for a linear channel (Fig. 2.3c).

2.3.6 Channel routing

Various methods of channel routing have been proposed for solving the problem of predicting the outflow hydrograph at a downstream point on the basis of the hydraulic properties of the channel and a known inflow at an upstream point (Yevjevich, 1964).

The \textit{lag and route} method (Meyer, 1941) is a linear two-parameter model which assumes that the storage, \( S \), at any time is taken to be proportional to the outflow which occurs after the elapse of a time lag, \( rc \). Thus,

\[ S(t) = Kc \cdot Q(t + rc) \]  \hspace{1cm} (2.16)

where \( Kc \) is the storage coefficient of the channel. Substituting Eq. 2.16 in the continuity equation (Eq. 2.2) yields

\[ P(t) = Q(t) + Kc \frac{d}{dt} Q(t + rc) \]  \hspace{1cm} (2.17)
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The impulse response function for this model is

\[ G(t) = \begin{cases} \frac{1}{Kc} e^{-(t-\tau c)/Kc} & \text{for } t > \tau c \\ 0 & \text{for } t \leq \tau c \end{cases} \] (2.18)

2.4 Summary

The conversion process of rainfall excess into direct surface runoff is described by the convolution integral and an instantaneous unit hydrograph in a surface runoff system which is assumed to be linear. The next chapter will introduce CELLMOD, the rainfall–runoff model which is based on the above theorems.
Chapter 3

DESCRIPTION OF CELLMOD

3.1 Introduction

This chapter will introduce the general outline of CELLMOD, a semi-distributed cell model for conversion of rainfall into runoff. The current modified version of CELLMOD has three previous versions: Diskin and Simpson (1978), Diskin et al. (1984) and Diskin (unpublished) which include examples and applications. The unpublished version, on which the present research is based, was developed by Dr. M. H. Diskin at the USDA-ARS Watershed Research Center in Tucson, Arizona in 1984.

3.2 The history of CELLMOD

The original version of CELLMOD (Diskin and Simpson, 1978) was developed as a quasi-linear, parametric, spatially semi-distributed routing model for converting rainfall excess into direct surface runoff. The model consists of a series of cascading reservoirs, termed model cells, each of which represents a portion of the basin. The interconnection between the cells rep-
CHAPTER 3. DESCRIPTION OF CELLMOD

represents the branching drainage pattern and the topographic features of the watershed, forming a tree-like structure. Two types of cells are simulated in the model: (1) exterior cells which receive as an input only the rainfall excess over the area represented by the cell; and (2) interior cells which receive both rainfall excess and channel inflow as inputs.

The main modification in the Diskin et al. (1984) version is the distinction between two types of inputs to the interior cells – the rainfall excess and the channel inflow at the upstream end of the stream through this area. Consequently, different routing procedures are used in the modified version to obtain the outputs from these two inputs. The channel outflow hydrograph from the upstream cell to the next downstream cell is the sum of these outputs.

In the third version of CELLMOD (Diskin, unpublished 1984) new procedures were added to take into account the specific conditions of a semi-arid environment. One condition considered is the high spatial variability of the rainfall over semi-arid watersheds. The revised procedures compute the rainfall excess input for each cell from the total rainfall data for one or several rain gages in and near the watershed. Another new procedure simulates the channel losses (infiltration of streamflow into channel bed and banks) in each cell.

3.3 The current version of CELLMOD

The following modifications were done in the program during the present study:

1. As discussed previously a system is said to be linear time-invariant if its parameters do not change with time. In the earlier versions
the storage parameter or any other parameter was allowed to vary from storm to storm, thus a quasi-linear model was obtained which accounted for some nonlinearities of the system (Diskin and Simpson, 1978). The varied parameter was used to calibrate the model in the fitting procedure. In the current version, an antecedent precipitation index (API) procedure was developed to calculate the soil moisture deficit prior to the event of interest. The model still uses a different value of the soil moisture deficit for each event, however this parameter is now related to the physical condition of the basin rather than being an arbitrary fitting parameter.

2. The infiltration procedure has been replaced by a solution to the Green and Ampt infiltration equation to compute values of rainfall excess under unsteady rainfall conditions. The parameters for this model have a more physical significance and are obtained from the soil properties.

3. In the older versions the spatial distribution was developed only for different rainfall inputs over each model cell, and all the other parameters were lumped over the entire watershed. In the modified version all the parameters are estimated from the soil characteristics and thus can vary over the watershed. They can be measured in the field and/or estimated from remotely sensed data.

4. The computer program CELLMOD is written in FORTRAN 77 (Appendix A). Initially the program was developed to be run on a main frame computer such as the CDC CYBER. During the present study, the program was modified to run on a mini-computer (VAX 11/780) and also on a IBM-PC type micro-computer with 640K of random
access memory (RAM). Because the FORTRAN compiler for small computers allows only 64K RAM memory for local variables, dummy commons were used in order to provide the required memory. The current version of CELLMOD is designed to work with up to 40 rain gages, a maximum of 40 model cells, up to 4 upstream cells and 300 time steps, at the most. However these numbers can be increased by a simple change in the format statement.

3.4 General outline of the model

3.4.1 The structure of the model

The model consists of a series of inter-connected cell units, each representing a specific portion of the area of the entire watershed. The interconnection between the cells form a tree-like structure which reflects the main drainage pattern and the topography of the basin. Each cell may be connected to and be receiving runoff from one or more cells upstream but it is connected and drains to only one cell downstream. An example of the branching structure of a hypothetical watershed with subunits is given in Fig. 3.1 along with a schematic model. Two types of cells can be distinguished: exterior cells and interior cells.

The exterior cell has no channel inflow and is usually, but not necessarily, located on the watershed divide. Exterior cells in Fig. 3.1 are 1, 3, 5, 8, 9 and 11. Cell 8, for example, is located internally in the watershed but with absence of channel inflow it is classified as exterior cell. Because there is no channel inflow into an exterior cell the rainfall excess hyetograph over the cell area is the only input.

The interior cell has one or more channels inflowing across its boundary.
Exterior Cells: 1,3,5,8,9,11
Single Channel Input Interior Cells: 2,4,7,12
Multiple Channel Interior Input Interior Cells: 6,10,13

Figure 3.1: Deviation of a hypothetical watershed into cell units and the schematic model of the watershed.
CHAPTER 3. DESCRIPTION OF CELLMOD

Cells numbered 2, 4, 6, 7, 10, 12 and 13 in Fig. 3.1 represent this type which can be subdivided into single channel input interior cells (cells number 2, 4, 7 and 12) and multiple channel input interior cells (cells number 6, 10 and 13). An interior cell receives as inputs both the rainfall excess hyetograph over the cell area and the inflow hydrographs from upstream channels. In the case of the multiple channel inflow cell, the channel inflow hydrograph is taken to be the sum of the outputs of the adjacent upstream cells.

Each model cell is composed of a number of elements that transform the cell's inputs into a single output in the form of a cell output hydrograph which is the sum of the surface outflow hydrograph and the channel output hydrograph. The program starts with the upstream exterior cells, and proceeds to the downstream cells. The outputs from output cells are used as input to adjacent downstream cells. In an interior cell with multiple inflows, all the inflow hydrographs are added together to form a single input hydrograph which is routed through the cell by the same method as in the case of a single channel inflow. The computation ends in the downstream cell nearest to the outlet of the watershed.

All the cells have the same internal structure in terms of the elements that make up the cell and their interaction producing the cell output. This enables the user to work with only one set of parameters, termed model parameters, for all the cells. Each of the parameters is assigned to an individual cell by a representative value, termed cell parameter, which relates to the area of the cell or the length of the channel within the cell relative to the average cell area or average channel length. The unique structure of this model helps with the optimization and calibration procedures. However, when the spatial distribution of one or more parameters is known, the model can accept individual values for each cell.
3.4.2 Computation of rainfall excess

The conversion of the total rainfall to rainfall excess for each gage is accomplished by using the infiltration equation proposed by Green and Ampt (1911). This model was modified for calculating infiltration and/or rainfall excess under steady rainfall conditions by Mein and Larson (1971; 1973) and later extended to unsteady rainfall conditions by Chu (1978).

The complete procedure for calculating the rainfall excess under unsteady rainfall will be discussed later in Chapter 4. The proposed model has six parameters which are reduced to only two operative parameters: (1) the saturated hydraulic conductivity, $K_s [L/T]$, which is calculated from the field estimation of the saturated conductivity, the canopy cover and the ground cover of the area represented by the rain gage; and (2) the effective matric potential, $SM [L]$, which is calculated from the soil texture and the residual soil moisture.

The residual moisture is calculated outside CELLMOD by an API-type model. The procedure will be described later in Chapter 5. The index is based on the daily rainfall data prior to a particular event. Only its final product, the residual soil moisture values for each area represented by a rain gage, is transferred to CELLMOD.

The rainfall excess is computed separately for each rain gage for which data are available. Therefore, the rainfall excess data are initially applied for areas defined by a Thiessen weighting procedure. The transformation of the rainfall excess from the Thiessen polygons to appropriate model cells is done by overlaying the polygons on the cells. This procedure, explained in detail in Chapter 6, is applied to each time interval for which rainfall data are available, resulting in an individual rainfall excess hydrograph for
CHAPTER 3. DESCRIPTION OF CELLMOD

each cell in the model.

3.4.3 Conversion of rainfall excess to surface outflow

The rainfall excess function for each cell is converted to a surface outflow hydrograph by routing it through a pair of unequal linear reservoirs in series (Fig. 3.2). The two reservoirs represent the combined action of overland flow and local channel flow within the area represented by the cell. In order to keep the number of model parameters to a minimum, two assumptions have been made:

1. The storage coefficient of one reservoir is taken arbitrarily to be 0.1 of the value of the coefficient for the second reservoir, thus

$$K_2 = 0.1K_1$$  (3.1)

2. The value of the storage coefficient is assumed to be proportional to the square root of the area represented by the cell, thus

$$K = AKC\sqrt{\frac{AC(j)}{AM}}$$  (3.2)

where AM is the area of a cell of average size $[L^2]$, $AC(j)$ represents the area of individual cell $j$ $[L^2]$, $AKC$ is the storage coefficient model parameter for the cell of average size $[T]$ and $K$ is the corresponding storage coefficient cell parameter.

The actual operation of conversion of rainfall excess to surface outflow for each cell is carried out by a numerical convolution procedure involving a unit hydrograph $U(t)$ derived from Eq. 2.11 for a pair of unequal linear...
Figure 3.2: Overland flow routing of rainfall excess input through cell units.
reservoirs in series:

\[ U(t) = \int_0^t \frac{1}{K_1} e^{-r/K_1} \frac{1}{K_2} e^{-\left(t-r\right)/K_2} \, dr = \]

\[ \frac{e^{-t/K_1} - e^{-t/K_2}}{K_1 - K_2} \quad (3.3) \]

Introducing Eq. 3.1 to Eq. 3.3 yields

\[ U(t) = \frac{e^{-t/K_1} - e^{-10t/K_1}}{0.9K_1} \quad (3.4) \]

Note that the hydrograph which is described by Eq. 3.3 or by Eq. 3.4 has a more realistic shape than the one described by Eq. 2.9 because it includes the rising limb.

Values of this function are evaluated at the end of each time increment (DT), then multiplied by values of the depth of rainfall excess for the corresponding time intervals. The products are summed up according to the numerical convolution procedure which results in a surface outflow hydrograph for each cell. The hydrograph is specified in terms of the ordinates at the end of each time interval.

The surface outflow hydrograph for each interior cell is combined with the channel outflow hydrographs of that cell to form the total cell outflow hydrograph. This outflow hydrograph becomes a part of the channel inflow hydrograph of the next cell immediately downstream of the cell considered, or the entire channel inflow hydrograph if this next cell is a single channel inflow cell.

### 3.4.4 Routing the channel inflow

The total channel inflow hydrograph for an interior cell is equal to the total cell outflow hydrograph or the sum of such hydrographs for the contributing cells immediately upstream of the cell considered. The channel inflow
CHAPTER 3. DESCRIPTION OF CELLMOD

hydrograph is routed through a pair of elements representing a linear channel and a linear reservoir in series (Fig. 3.3). The routed hydrograph is then subjected to a channel loss element which subtracts the channel losses from the routed hydrograph (Fig. 3.3). The remaining part of the routed hydrograph, after subtracting the channel losses, forms the channel outflow component of the interior cell. The other component of the total cell output is the surface runoff derived from rainfall excess for the cell.

Routing is accomplished by a linear reservoir routing subroutine using a storage coefficient \( K_c \) \([T]\), followed by a forward time shift, \( \tau_c \) \([T]\), of the linear reservoir \([T]\). The value of the two parameters of the routing operation are assumed to be proportional to the length of the channel in the interior cell considered. The values are derived from the corresponding model parameters by the following expressions

\[
K_c = \frac{T_{KF} \cdot LC(j)}{LM} \tag{3.5}
\]

and

\[
\tau_c = \frac{T_{DF} \cdot LC(j)}{LM} \tag{3.6}
\]

where \( LC(j) \) and \( LM \) are respectively the individual channel length of each cell and the mean channel length for all cells. The storage coefficient and the time shift for a cell with an average channel length are represented by the model parameters \( T_{KF} \) and \( T_{DF} \), respectively.

An example of the routing operation is shown schematically in Fig. 3.4. The outflow hydrograph has a lower peak and a longer time base in comparison to the peak and duration of the inflow hydrograph. In addition, it is shifted forward in time by the time interval \( \tau_c \). It should be noted that the time shift does not have to be an integer multiple of the time step \( DT \) used in the computation for rainfall increments. The program includes
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CHANNEL INFLOW

$K_c$ — Channel Storage Coefficient [T]

$\tau_c$ — Time Shift [T]

Kc — Channel Storage Coefficient [T]

CHANNEL LOSS ELEMENT

CHANNEL OUTFLOW

Figure 3.3: Routing of channel inflow input through cells and location of channel loss element.
Figure 3.4: Typical channel inflow and outflow hydrographs for channel routing operation.
an interpolation procedure that calculates, by linear interpolation, the ordinates of the outflow hydrograph at equally spaced time intervals, $DT$, starting at the time origin used for all computations.

The combined operation of the reservoir routing and the time shifting described above for each of the cells is equivalent to convolution of the channel inflow hydrograph of that cell and a unit impulse response function, $G(t)$, expressed by Eq. 2.18. The convolution integral is similar to one described in Eq. 3.3 for routing a pair of unequal linear reservoirs in series, however here the convolution is between a linear reservoir and a linear channel.

$$G(t) = \int_0^t \frac{1}{K} e^{-\tau c/K} \frac{1}{Kc} e^{-(t-\tau c)/Kc} d\tau c = \frac{e^{-t/K} - e^{-t/Kc}}{K - Kc} \tag{3.7}$$

3.4.5 Subtracting of channel losses

Channel losses are computed individually for each interior cell. The channel losses are subtracted from the channel hydrograph after it is routed through the linear channel and linear reservoir combination (Fig. 3.3). The channel loss operation for each cell is thus assumed to be lumped near the outlet of the cell, after the routing operation and before the channel outflow is combined with the surface outflow to form the total cell output.

The channel loss operation consists of subtracting two components from the routed channel hydrograph (Fig. 3.5a). One part is a constant rate of loss for the cell considered and the second is a variable rate which decreases exponentially from an initial value throughout the occurrence of runoff in the routed hydrograph. The output of the channel loss operation is the part of the routed hydrograph which is in excess of the sum of the two
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(a) Inflow Hydrograph

QCA — Constant Channel Loss
PLS — Initial Loss Ratio
QKS — Loss Decay Factor

(b) Outflow Hydrograph

Figure 3.5: Procedure used for subtracting channel losses.
The constant rate of channel loss is taken to be proportional to the length of the channel in the cell considered. The value of this loss, $Q_{MC}$ \([L^3/T]\) is computed by

$$\frac{Q_{MC} = \frac{QCA \cdot LC(j)}{LM}}$$

where $LC(j)$ and $LM$ are, respectively, the individual channel length of each cell and the mean channel length for all cells. The model parameter $QCA$ represents the constant channel loss for a cell with average channel length.

The variable part of the channel losses is taken to have an initial value, $QLC$, which is a fixed proportion of the magnitude of the peak flow less the constant channel loss of the routed channel flow hydrograph. The magnitude of this initial loss is given by

$$QLC = PLS \cdot (QMX - QMC)$$

where $QMX$ is the maximum value of the routed channel hydrograph \([L^3/T]\). The model parameter $PLS$ is a dimensionless quantity restricted to be between zero and one \((0.0 < PLS < 1.0)\). Each of the subsequent values of the variable channel loss is derived from the value preceding it by multiplying the previous value by a constant multiplier, $QKS$. The variable loss rate, $QLT$, is thus given by

$$QLT(i) = QKS \cdot QLT(i - 1)$$

where the initial parameter, $QKS$, is restricted to be in the range between zero and one \((0.0 \leq QKS \leq 1.0)\), and where the initial value of the variable loss rate (for $i = 1$) is computed from the initial value computed above

$$QLT(1) = QKS \cdot QLC$$
CHAPTER 3. DESCRIPTION OF CELLMOD

The total channel losses at the end of each time increment is equal to the sum of the constant loss \( Q_{MC} \) and the variable channel loss \( Q_{CT} \) for that time increment. The channel outflow hydrograph for the cell considered (Fig. 3.5b) is the remaining part of the routed channel hydrograph after subtracting the two channel loss components.

3.5 Summary

CELLMOD is essentially a spatial distributed parametric routing model for conversion of rainfall into runoff. The watershed is divided into cell units which are interconnected in a tree–like structure reflecting the main drainage pattern. The computation of the rainfall excess is based on the solution to the Green and Ampt equation for unsteady rainfall conditions. The rainfall excess input is transformed into a corresponding output by routing it through a pair of unequal linear reservoirs in series. These two reservoirs represent the overland flow and the local channel flow. The total channel routing is simulated by convolution between linear reservoir and linear channel. A special procedure simulates the channel losses.
Chapter 4

THE RAINFALL EXCESS CALCULATION

4.1 Introduction

The rainfall excess calculation used in the rainfall–runoff model is based on the solution for the Green and Ampt infiltration equation for unsteady rainfall conditions. The procedure discussed below uses the rainfall information in terms of actual time pattern of rainfall intensity and the soil properties and improves significantly the prediction of infiltration and runoff.

4.2 The Green and Ampt infiltration model

A physically–based infiltration model, applying Darcy’s law, was proposed by Green and Ampt (1911). The model is a simplification of the infiltration process in the field during a rainfall event, and is based on the following assumptions:

1. The infiltration starts from a ponded surface.
2. A homogeneous soil profile.

3. Uniform distribution of initial water content.

4. The water enters the soil as slug flow, resulting in a sharp discontinuity (wetting front) which separates the soil profile into higher moisture content in the upper zone above the originally dry soil zone (Fig. 4.1).

5. As infiltration progresses, the movement of the water is in the form of an advancing wetting front.

6. There is only vertical movement of water down the profile without any soil moisture diffusion.

7. The spatial distributions of the rainfall, topographical features and the soil type are uniform.

The one-dimensional form of Darcy's law may be written as:

\[ f = \frac{K_s(H'' - H')}{L_F} \]  \hspace{1cm} (4.1)

where \( f \) is the infiltration rate \([L/T]\), \( K_s \) is the hydraulic conductivity at the transmission zone \([L/T]\), \( L_F \) is the distance from the surface to the wetting front \([L]\), \( H' \) is the total head immediately below the discontinuous wetting front \([L]\) which is numerically equal to the capillary suction, \( S \), and \( H'' \) is the total head at the top of the column \([L]\), which is given by:

\[ H'' = L_F + H_o \]  \hspace{1cm} (4.2)

where \( H_o \) \([L]\) is the depth of water ponded on the surface. Consequently, Eq. 4.1 can be written as:

\[ f = \frac{K_s(H_o + S + L_F)}{L_F} \]  \hspace{1cm} (4.3)
the Green and Ampt infiltration equation.

By continuity, the cumulative infiltration, $F$, $[L]$ is the product of the distance to the wetting front and the initial soil moisture deficit for the range of soil moisture, $M$ $[L^3/L^3]$, which is equivalent to the fillable porosity. The soil moisture deficit is the difference between the initial, $\theta_i$, and the saturated volumetric water content, $\theta_s$. Thus, $F$ can be written as:

$$ F = M \cdot L_F = (\theta_s - \theta_i) L_F $$  \hspace{1cm} (4.4)

Assuming that the depth of water ponded on the surface approaches zero and introducing Eq. 4.4 into Eq. 4.3, yields

$$ \frac{dF}{dt} = f = K_s + \frac{K_s \cdot MS}{F} $$  \hspace{1cm} (4.5)

Differentiating $F$ with respect to the time, $t$, and integrating by separation of variables with the condition $F = 0$ at $t = 0$, Eq. 4.5 becomes

$$ K_s \cdot t = F - SM \cdot \ln\left(\frac{1 + F}{SM}\right) $$  \hspace{1cm} (4.6)

### 4.3 Derivation of infiltration model for unsteady rainfall

The Green and Ampt infiltration model, as represented by Eq. 4.6, relates the cumulative infiltration depth to the time from the start of infiltration. Recalling assumption 1 from above, Eq. 4.6 expects a ponded surface at the beginning of the infiltration process which means a saturated surface at time zero. Consequently, the infiltration rate, $f$, is always equal to the infiltration capacity, $f_p$, $[L/T]$. Mein and Larson (1973) suggested that in most rainfall events there is at least a brief period, before runoff starts, in which all the rainfall infiltrates into the ground (Fig. 4.2).
Figure 4.1: Schematic diagram of Green and Ampt model (after Skaggs and Khaleel, 1982).

Figure 4.2: Schematic diagram of rainfall, infiltration and rainfall excess rates as a function of time (after Mein and Larson, 1971).
According to the above authors, the infiltration process can be described in two distinct stages. During the first stage the rainfall rate is greater than the saturated conductivity, but less than the infiltration capacity. All the rainfall infiltrates into the ground and the soil moisture in the top soil layer increases. At the moment when the rainfall intensity is greater than the infiltration capacity the second stage begins. This moment is referred to as the time of surface saturation, or the surface ponding time, and from then on runoff occurs. The time of surface ponding, $t_p$, is a function of the rainfall rate, it is shorter for higher rainfall rates as presented by lines 1, 2 and 3 in Fig. 4.3.

![Infiltration curves for different rainfall intensities](image)

Figure 4.3: Infiltration curves for different rainfall intensities (after Mein and Larson, 1971).

As the rainfall continues, the infiltration rate decreases with time and approaches the saturated hydraulic conductivity. In the case when the rainfall rate is less than saturated hydraulic conductivity, infiltration may
continue indefinitely at the same rate as the rainfall rate without surface saturation (line 4, Fig. 4.2).

By applying Darcy’s law Mein and Larson (1973) developed a modified version of the infiltration rate equations for the two stages discussed above and for a steady rainfall \( P \). They expressed the infiltration equations as:

1. for \( t < t_p \), \( f = P \) and
\[
F_s = \frac{S_{av} \cdot M}{P/K_s - 1}
\]  
where \( F_s \) refers to infiltration depth prior to runoff and \( S_{av} \), which replaces \( S \) in Eq. 4.5, is the average capillary suction at the wetting front and is obtained by integrating the suction with respect to the relative conductivity.

2. for \( t > t_p \), \( f = f_p \) given by:
\[
f_p = K_s + \frac{K_s \cdot S_{av} \cdot M}{F}
\]  

Using the same approach and similar analysis, Chu (1978) extended the model which had been developed by Mein and Larson for rainfall events with unsteady intensity. Using calculation techniques, the Green and Ampt equations are applied to determine the time separating the surface ponding stage and the unponding stage so that the infiltration for each stage can be treated separately.

The steady rainfall model includes two stages at most: first is the unponded surface stage which is followed by the surface ponding stage. The latter, if it occurs, continues till the end of the rainfall event. In contrast to the steady rainfall model, the unsteady rainfall model can handle more than one period for each stage. The infiltration process can switch from one stage to the other.
4.4 Selection of parameters for the Green and Ampt model

Three parameters are involved in the Green and Ampt model described by Eq. 4.5: (1) the saturated or final hydraulic conductivity, $K_s$ [L/T]; (2) the difference in the average effective capillary potential across the wetting front, $S$, [L]; and (3) difference in average soil moisture across the wetting front, $M$ [L/T]. These parameters require knowledge about the soil characteristics of the area under consideration. The $S$ and $M$ parameters usually appear together under the term 'effective matric potential' denoted as $SM$, and are treated as one parameter (Chu, 1978). In this study these two parameters are estimated separately until the final computation.

The following sections will review the theoretical background for determining the above parameters.

4.4.1 Saturated hydraulic conductivity

Estimation of the saturated hydraulic conductivity is based on empirical relationships between: (1) the field estimation of the saturated hydraulic conductivity for bare soil, $K_{s\bar{b}}$; (2) the percent of canopy cover, $CC$; and (3) the percent of ground cover, $GC$, which includes all the surface coarse fragments (the soil material larger than 2 mm). The relationships have been formulated as (Lane, personal communication):

$$K_s = K_{s\bar{b}} \cdot e^{CC} \cdot e^{GC}$$  \hspace{1cm} (4.9)

These relationships reflect the theory that the infiltration increases as a function of higher vegetation density and/or higher rock cover on the soil surface. These relationships have been found to fit field data from the Walnut Gulch area in southeastern Arizona (Lane, unpublished).
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Estimation of the hydraulic conductivity of bare soil

The field saturated hydraulic conductivity for bare soil, $K_f$, has been obtained from the SCS soil survey. The $K_f$ values have been estimated in the field by a method described in Libardi et al. (1980). However, Bouwer (1966, 1969) found that as a result of entrapped air in the ground the $K_{sbar}$ for the Green and Ampt model should not be the full saturated conductivity but has to be replaced by the effective conductivity (or resaturated hydraulic conductivity) which is the wetting conductivity at residual air saturation. Thus,

$$K_{sbar} = 0.5K_f$$

This study follows Bouwer's suggestion that the effective hydraulic conductivity is one half of the field saturated hydraulic conductivity for bare soil obtained by the SCS soil survey.

Rawls et al. (1983), as a result of analyzing approximately 5000 soil horizons, found that the soil texture classes are the most significant discriminator of the Green and Ampt parameters. They suggested default values for $K_{sbar}$ for the 11 USDA soil texture classifications (Table 4.1) which can be used when applying the Green and Ampt model using soil survey data.

Estimation of canopy cover

The technique for estimating the canopy cover used large scale aerial photographs. The aircraft flew at about 1,500 m above ground and covered the study area in six passes. From this height it is possible to recognize small bushes and shrubs.
The photographs were processed using a Datacolor/Edge Enhance System. This system combines analog computer program and closed circuit television techniques to produce both color enhancement and edge or line enhancement of photographic transparencies. The photographic records contain information measured in terms of photographic density produced by shades of gray in the films. The radiograph is illuminated by a light box and scanned by a high-performance television camera. The computer program calculates the density gradient (rate of change of photographic density). The result of the computation, the enhanced picture, is displayed on the black and white television screen.

The video signal from the camera is also processed by the color analyzer, which converts the camera signal to a signal that is proportional to the film density. The gray scale or photographic density is divided into as many as twelve levels or intervals. Each level is shown on the color monitor as one of twelve different colors and on the black and white monitor as twelve different discrete shades of gray. The computer program has the capability to reduce the number of colors by replacing any color with black and measuring the percent area of the color.

For example, the vegetation appears on the TV monitor in two tones of green. By eliminating the other ten colors, the percent of area in green, which is actually the percent of canopy cover in the area detected by the photograph, is determined.

Estimation of ground cover

The ground cover percentage estimation procedure is a combination of the data supplied by the SCS soil survey and ground-level photography.

The SCS soil survey provides information about the soil texture in each
of the soil series of Walnut Gulch differentiated by the horizons of the soil profile. It also provides information about the percent by weight of the coarse fragments (the soil material larger than 2 mm), $M_r$, and the bulk density, $BD$, for the entire soil texture range $[M/L^3]$.

The soil porosity, $n$ [%], is calculated by the following equation (Hillel, 1971):

$$n = \frac{100(BD_8 - BD)}{BD_8} \quad (4.11)$$

where $BD_8$ is the bulk density of the soil solid fraction which is equal to 2.65 gr/cm$^3$. Thus, the percent by volume of the solid fraction, $V_s$, is

$$V_s = 100 - n \quad (4.12)$$

and the percent by volume of the coarse fragments (rock content), $V_r$, is given by:

$$V_r = V_s \cdot M_r \quad (4.13)$$

Introducing Eq. 4.11 and Eq. 4.12 into Eq. 4.13 yields:

$$V_r = M_r \frac{100 - 100(BD_8 - BD)}{BD_8} \quad (4.14)$$

The study is actually looking for the percent of ground cover, $GC$, i.e. percent by area rather than the percent by volume. However, because the upper soil horizon – A or A1 – is usually between 2 to 5 cm in depth, the percent by volume values are used as a first approximation of the GC. Table 4.2 presents the estimated ground cover [%] for the study area from the soil survey data and those calculated using the procedure described by Eq. 4.14.

Soil survey data provide a good measure of the spatial variation of the soils in the study area. However, these data depend on a relatively
CHAPTER 4. THE RAINFALL EXCESS CALCULATION

Table 4.1: Default values for the saturated hydraulic conductivity for bare soil (after Rawls et al., 1983).

<table>
<thead>
<tr>
<th>Soil Texture Class</th>
<th>Saturated Hydraulic Conductivity for Bare Soil (mm/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand</td>
<td>118.0</td>
</tr>
<tr>
<td>Loamy Sand</td>
<td>30.0</td>
</tr>
<tr>
<td>Sandy Loam</td>
<td>11.0</td>
</tr>
<tr>
<td>Loam</td>
<td>6.5</td>
</tr>
<tr>
<td>Silt Loam</td>
<td>3.4</td>
</tr>
<tr>
<td>Silt</td>
<td>2.5</td>
</tr>
<tr>
<td>Sandy Clay Loam</td>
<td>1.5</td>
</tr>
<tr>
<td>Clay Loam</td>
<td>1.0</td>
</tr>
<tr>
<td>Silty Clay Loam</td>
<td>0.9</td>
</tr>
<tr>
<td>Sandy Clay</td>
<td>0.6</td>
</tr>
<tr>
<td>Silty Clay</td>
<td>0.5</td>
</tr>
<tr>
<td>Clay</td>
<td>0.4</td>
</tr>
</tbody>
</table>

Table 4.2: Estimation of ground cover [%] for Watersheds 8 and 11 from the soil survey data.

<table>
<thead>
<tr>
<th>Mapping No.</th>
<th>Padom No.</th>
<th>Series Name</th>
<th>Soil Horizon</th>
<th>Soil Bulk Density (cm)(gr/cm^3)</th>
<th>Coarse Fragments (% wt.)</th>
<th>Ground Cover (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>40,41</td>
<td>79</td>
<td>Tombstone I</td>
<td>Al</td>
<td>2.0</td>
<td>1.64</td>
<td>57.3</td>
</tr>
<tr>
<td>50</td>
<td>75</td>
<td>Abrigo</td>
<td>A</td>
<td>5.0</td>
<td>1.49</td>
<td>50.2</td>
</tr>
<tr>
<td>90,91</td>
<td>74</td>
<td>Nolan</td>
<td>Al</td>
<td>1.0</td>
<td>1.72</td>
<td>46.8</td>
</tr>
<tr>
<td>100,101</td>
<td>81</td>
<td>Cazador</td>
<td>A</td>
<td>5.0</td>
<td>1.74</td>
<td>30.4</td>
</tr>
<tr>
<td>120</td>
<td>82</td>
<td>Bascal</td>
<td>Al</td>
<td>5.0</td>
<td>1.52</td>
<td>10.5</td>
</tr>
<tr>
<td>180</td>
<td>78</td>
<td>Tierrangaue</td>
<td>Al</td>
<td>5.0</td>
<td>1.67</td>
<td>9.7</td>
</tr>
<tr>
<td>210,211</td>
<td>91</td>
<td>Tombstone II</td>
<td>Al</td>
<td>8.0</td>
<td>1.75</td>
<td>52.6</td>
</tr>
</tbody>
</table>
small number of sampling points with interpretation as mapping units using aerial photographs and additional knowledge about the soil variations with relation to slope and aspect. In order to overcome this disadvantage, 179 ground-level (about 1.5 m high) color photographs of the soil surface were taken in the study area along six transects using a 35 mm hand-held camera. Each sampling location was assigned to the soil series which had been defined and mapped by the soil survey. The results of the averaged values with statistics of the ground cover for each soil series is presented in Table 4.3. This procedure takes advantage of the spatial variability of the soil series on one hand, and many more sampling locations on the other hand.

Interpretation of the photographs was done by using the Datacolor/Edge Enhance System with the same procedure as described previously for the canopy cover. A high correlation ($r^2 = 0.94$) was computed between the percent of ground cover obtained by the two methods (Fig. 4.4). However, it can be seen that the photographic ground cover has higher estimated values than the soil survey estimation. One of the explanations can be that the difference between the two methods is a result of surface erosion which exposed the coarse fragments on the soil surface.

4.4.2 Effective matric potential

As mentioned previously the effective matric potential, $SM$, was broken down into two parameters: the difference in the average capillary potential suction across the wetting front, $S \ [L]$, and the difference in the average soil moisture across the wetting front, $M \ [L^3/L^3]$.

The parameter, $S$, which depends on the soil texture, is a product of the average potential across the wetting front, $S_f \ [L]$, and the effective porosity
Figure 4.4: Correlation between the ground cover estimated by the soil survey data vs. ground-level photographs.
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\[ S = S_f \cdot n_e \]  \hspace{1cm} (4.15)

The effective porosity is assumed to be 0.9 of the soil porosity (Onstad et al., 1973; Brackensiek and Onstad, 1977). Recalling Eq. 4.4, the parameter, \( M \), is a function of both the soil texture and the residual soil moisture:

\[ M = \theta_s - \theta_i = 1 - S_e \]  \hspace{1cm} (4.16)

where \( \theta_s \) and \( \theta_i \) are the saturated and initial volumetric water content \([L^3/L^3]\), respectively. \( S_e \) is the relative effective saturation \([0 \leq S_e \leq 1]\).

The effective matric potential, \( SM \), is the product of Eq. 4.15 and Eq. 4.16:

\[ SM = S_f \cdot n_e (1 - S_e) \]  \hspace{1cm} (4.17)

Lane (unpublished) compiled data from various sources and suggested default values for the above parameters for each soil texture class (Table 4.4). These values can be used, in the absence of other data, to estimate the effective matric potential. However, it can be seen from the table that there is no unique solution for \( SM \) because of its relation to the residual soil moisture at a particular time.

The SCS soil survey defined sandy-loam as the only texture class for the study area, consequently for the present research the parameters \( S_f, n_e \) and therefore also \( S \) are assumed to be lumped for the whole area. These values were obtained from Table 4.4.

The relative effective saturation, \( S_e \), on the other hand, is assumed to vary both spatially and temporally. Its values are obtained from an API-type model for each of the rain gages in the study area. A full description of the API model and the results are presented in the next chapter.
CHAPTER 4. THE RAINFALL EXCESS CALCULATION

Table 4.3: Photographic analyses of ground cover [%] for Watersheds 8 and 11.

<table>
<thead>
<tr>
<th>Mapping No.</th>
<th>Padom No.</th>
<th>Series Name</th>
<th>Number of Photos</th>
<th>Average Photographic Ground Cover (%)</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>40,41</td>
<td>79</td>
<td>Tombstone I</td>
<td>32</td>
<td>44.375</td>
<td>5.325</td>
</tr>
<tr>
<td>50</td>
<td>75</td>
<td>Abrigo</td>
<td>12</td>
<td>36.660</td>
<td>5.132</td>
</tr>
<tr>
<td>90,91</td>
<td>74</td>
<td>Nolan</td>
<td>8</td>
<td>37.003</td>
<td>4.810</td>
</tr>
<tr>
<td>100,101</td>
<td>81</td>
<td>Cazador</td>
<td>38</td>
<td>28.001</td>
<td>7.369</td>
</tr>
<tr>
<td>120</td>
<td>82</td>
<td>Bascal</td>
<td>54</td>
<td>12.825</td>
<td>4.112</td>
</tr>
<tr>
<td>180</td>
<td>78</td>
<td>Tierrangre</td>
<td>22</td>
<td>9.221</td>
<td>3.753</td>
</tr>
<tr>
<td>210,211</td>
<td>91</td>
<td>Tombstone II</td>
<td>26</td>
<td>35.247</td>
<td>6.344</td>
</tr>
</tbody>
</table>

Table 4.4: Default values for the Green and Ampt parameters for bare soil plot (after Lane, unpublished). -1/3 bar and -15 bar refers to the field capacity and the wilting point, respectively.

<table>
<thead>
<tr>
<th>Soil Texture Class</th>
<th>Eff. Porosity (%)</th>
<th>Average Potent. (mm)</th>
<th>Relative Eff. Saturation at -1/3bar</th>
<th>Eff. potential at -1/3bar</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand</td>
<td>.40</td>
<td>49.</td>
<td>.22</td>
<td>15.3</td>
</tr>
<tr>
<td>Loamy Sand</td>
<td>.40</td>
<td>63.</td>
<td>.30</td>
<td>17.6</td>
</tr>
<tr>
<td>Sandy Loam</td>
<td>.41</td>
<td>90.</td>
<td>.49</td>
<td>18.8</td>
</tr>
<tr>
<td>Loam</td>
<td>.43</td>
<td>110.</td>
<td>.60</td>
<td>18.9</td>
</tr>
<tr>
<td>Silt Loam</td>
<td>.49</td>
<td>173.</td>
<td>.63</td>
<td>31.4</td>
</tr>
<tr>
<td>Silt</td>
<td>.42</td>
<td>190.</td>
<td>.67</td>
<td>26.3</td>
</tr>
<tr>
<td>Sandy Clay Loam</td>
<td>.35</td>
<td>214.</td>
<td>.77</td>
<td>17.2</td>
</tr>
<tr>
<td>Clay Loam</td>
<td>.31</td>
<td>230.</td>
<td>.89</td>
<td>7.2</td>
</tr>
<tr>
<td>Silty Clay Loam</td>
<td>.43</td>
<td>253.</td>
<td>.84</td>
<td>17.4</td>
</tr>
<tr>
<td>Sandy Clay</td>
<td>.32</td>
<td>260.</td>
<td>.78</td>
<td>18.3</td>
</tr>
<tr>
<td>Silty Clay</td>
<td>.42</td>
<td>288.</td>
<td>.87</td>
<td>15.7</td>
</tr>
<tr>
<td>Clay</td>
<td>.39</td>
<td>310.</td>
<td>.86</td>
<td>16.9</td>
</tr>
</tbody>
</table>
4.5 Example of the Green and Ampt infiltration model for unsteady rainfall

This section presents an example for the infiltration calculation using the Green and Ampt model for unsteady rainfall. Rainfall data for this example is obtained from rain gage No. 55 in Watershed 11 from the storm of July 30, 1966. The initial input parameters for the model are:

1. \( K_{s\text{bar}} \), saturated conductivity for bare soil = 17.000 \( mm/hr \). Data from the soil survey and using Eq. 4.10.

2. \( CC \), canopy cover = 6\%, obtain from air photographs.

3. \( GC \), ground cover = 44.4\%, obtained from ground level photographs.

4. \( n_{e} \), effective porosity = 41\%, from Table 4.4.

5. \( S_{f} \), average potential = 90 \( mm \), from Table 4.4.

6. \( S_{e} \), the relative effective saturation = 0.78, obtained from the API model.

Using Eq. 4.9 with parameters 1, 2 and 3 the saturated conductivity is calculated to be 28.134 \( mm/hr \). The effective matric potential is calculated to be 8.118 \( mm \), by using parameters 4, 5 and 6 in Eq. 4.17.

The results are presented in Fig 4.5 and Table 4.5. It can be seen that for this particular event the rainfall excess started 3 times when the rainfall rate exceeded the infiltration capacity in that particular time.
Figure 4.5: Rainfall rate, infiltration rate and rainfall excess rate as a function of time, results from the Green and Ampt model for unsteady rainfall.
Table 4.5: Rainfall excess calculations with Green and Ampt model for unsteady rainfall for raingage No. 55 on July 30, 1966.

<table>
<thead>
<tr>
<th>Time (min)</th>
<th>Rainfall Rate (mm/hr)</th>
<th>Rainfall Depth (mm)</th>
<th>Infiltration Rate (mm/hr)</th>
<th>Infiltration Depth (mm)</th>
<th>Rainfall Excess Rate (mm/hr)</th>
<th>Rainfall Excess Depth (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>12.19</td>
<td>0.00</td>
<td>12.19</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>3</td>
<td>20.83</td>
<td>0.61</td>
<td>20.83</td>
<td>0.61</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>6</td>
<td>45.72</td>
<td>1.65</td>
<td>45.72</td>
<td>1.65</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>9</td>
<td>55.88</td>
<td>3.94</td>
<td>55.88</td>
<td>3.94</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>12</td>
<td>27.94</td>
<td>6.73</td>
<td>27.94</td>
<td>6.73</td>
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<td>8.13</td>
<td>15.00</td>
<td>8.13</td>
<td>0.00</td>
<td>0.00</td>
</tr>
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<td>18</td>
<td>7.62</td>
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<td>8.88</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>21</td>
<td>38.10</td>
<td>9.26</td>
<td>38.10</td>
<td>9.26</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>24</td>
<td>38.10</td>
<td>11.16</td>
<td>38.10</td>
<td>11.16</td>
<td>0.00</td>
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<td>30</td>
<td>41.91</td>
<td>14.02</td>
<td>41.91</td>
<td>14.02</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>33</td>
<td>17.78</td>
<td>16.12</td>
<td>17.78</td>
<td>16.12</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>36</td>
<td>17.78</td>
<td>17.01</td>
<td>17.78</td>
<td>17.01</td>
<td>0.00</td>
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<td>17.90</td>
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</tr>
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</tr>
<tr>
<td>48</td>
<td>54.19</td>
<td>21.79</td>
<td>38.31</td>
<td>21.52</td>
<td>tp 15.88</td>
<td>0.27</td>
</tr>
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<td>51</td>
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<td>37.52</td>
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<td>1.07</td>
</tr>
<tr>
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<td>30.75</td>
<td>53.37</td>
<td>7.77</td>
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<td>34.98</td>
<td>32.52</td>
<td>108.95</td>
<td>10.43</td>
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<td>12.70</td>
<td>50.15</td>
<td>12.70</td>
<td>34.27</td>
<td>0.00</td>
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<td>50.79</td>
<td>12.70</td>
<td>34.91</td>
<td>0.00</td>
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</tr>
<tr>
<td>75</td>
<td>38.10</td>
<td>51.42</td>
<td>34.42</td>
<td>35.54</td>
<td>tp 3.68</td>
<td>15.88</td>
</tr>
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<td>78</td>
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<td>30.48</td>
<td>37.26</td>
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</tr>
<tr>
<td>81</td>
<td>19.98</td>
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<td>19.98</td>
<td>38.79</td>
<td>0.00</td>
<td>16.07</td>
</tr>
<tr>
<td>84</td>
<td>6.60</td>
<td>55.85</td>
<td>6.60</td>
<td>39.78</td>
<td>0.00</td>
<td>16.07</td>
</tr>
<tr>
<td>87</td>
<td>6.60</td>
<td>56.18</td>
<td>6.60</td>
<td>40.12</td>
<td>0.00</td>
<td>16.07</td>
</tr>
<tr>
<td>90</td>
<td>.00</td>
<td>56.51</td>
<td>.00</td>
<td>40.45</td>
<td>.00</td>
<td>16.07</td>
</tr>
</tbody>
</table>

tp = time to ponding
4.6 Conclusions

The Green and Ampt model was adapted in this study for calculating the rainfall excess under unsteady rainfall conditions. It appears that the model gives a good simulation of the actual process in the field. The model parameters have physical significance and can be computed from the soil properties.

Although six parameters are involved in the rainfall excess estimation procedure, their number is reduced to only two operative parameters for the calibration and optimization procedures.
Chapter 5

API–TYPE MODEL

5.1 Introduction

During a specific event the amount of rainfall excess resulting from a given rainfall depends upon many factors such as storm characteristics, soil characteristics and vegetation characteristics. Generally speaking, without taking into account the rainfall characteristics such as storm intensity, duration and areal distribution, the soil moisture deficit in the upper soil layer just before a rainfall event is perhaps the most important factor involved in the rainfall–runoff relationship because of its affect on the infiltration capacity (Richards and Strahl, 1971; Mein and Larson, 1971; Skaggs and Khaleel, 1982).

Both the capillary potential and the relative conductivity are determined by the soil moisture content. When the initial moisture content is low the capillary potential is high and the relative conductivity is small, and vice versa. Again, without accounting for the rainfall intensity, the runoff begins after the initial soil moisture deficit has been satisfied. The largest part of the rainfall which does not become runoff, especially for arid watersheds, is required to fill the soil moisture deficit and its influence is
CHAPTER 1. API–TYPE MODEL

greater at the beginning of the storm.

Many rainfall–runoff models use initial moisture deficit as one of the model parameters where the soil moisture is actually measured or estimated. Furthermore, for a forecasting rainfall–runoff model an objective procedure for evaluating the soil moisture deficit at the beginning of each storm event is a necessary condition (Richards and Strahl, 1971).

Rainfall characteristics are different for each storm but they can be determined accurately using an adequate network of rain gages or, as an alternative, meteorological radar. Most vegetation and soil characteristics, on the other hand, usually remain relatively constant with time except for seasonal variation. However, soil moisture content is highly variable and for many hydrologic analyses, soil moisture measurements are not available just prior to the rainfall event and have to be estimated. Several methods are used for estimating the antecedent soil moisture of a specific watershed:

1. Interpolation between soil moisture measurements in time and space domains.

2. Calculation of the water balance equation.

3. Using an antecedent precipitation index based mainly on daily rainfall.

Antecedent precipitation index (API) is a practical solution to the problem of estimating the initial moisture condition of a watershed because daily precipitation is usually the best and often the only available information.

The purpose of this chapter is to present an API–type model that has been derived from the original model suggested by Kohler and Linsley
(1951), to use the API-type model to predict the runoff from four experimental watersheds and to test results against the observed runoff. Note that the primary objective of the API derived model is to estimate the soil moisture deficit (rather than the runoff) in order to use it in a forecasting rainfall–runoff model such as CELLMOD.

1.2 Derivation of API model

Originally, the antecedent precipitation index was a single parameter model for runoff prediction assuming a logarithmic recession of soil moisture ($K$) during a period of no precipitation (Kohler and Linsley 1951):

$$I_t = I_0 \cdot K^t \tag{1.1}$$

where $I_0$ is the initial value of the soil moisture index [L] and $I_t$ is the reduced value $t$ days later [L]. The recession factor, $K$ [dimensionless, $0 < K < 1$] is related to the actual evapotranspiration and is affected by factors such as physiography, climate and vegetation of the watershed. Under the humid conditions of northeastern USA the value of $K$ varies between 0.85 and 0.98 (Linsley et al., 1982). According to Eq. 5.1, $K = 0.90$ means that following a dry day the soil moisture is 10% less than on the previous day. If rainfall occurred, the amount is added to the index. The index can also be written as:

$$I_t = I_0 \cdot e^{-K \cdot t} \tag{1.2}$$

The API of the form presented in Eqs. 5.1 or 5.2 is primarily useful for estimating soil moisture under no runoff conditions rather than prediction of the runoff itself. Furthermore, if the storm runoff is known, it is desirable to subtract its value from the rainfall for better estimation of the watershed recharge.
Saxton and Lenz (1967) distinguish between antecedent precipitation index (API) and antecedent retention index (ARI). The latter refers to the retention, which can be represented as precipitation, $P$, minus runoff, $QP$, when minor losses such as interception are negligible. Whatever the index name, to estimate both soil moisture and runoff from daily precipitation data, Eq. 5.2 can be written as:

$$I_t = (I_0 + P) \cdot e^{-Kt}$$

(5.3)

This equation is valid for the case when no runoff occurs. However, when runoff occurs, the runoff is subtracted from the precipitation and the recession curve starts from a threshold level defined as:

$$T = I_0 + (P - QP)$$

(5.4)

Thus, the index, for a runoff event, has the form:

$$I_t = (I_0 + (P - QP)) \cdot e^{-Kt}$$

(5.5)

By substituting Eq. 5.4 into Eq. 5.5 it can be shown that:

$$I_t = T \cdot e^{-Kt}$$

(5.6)

then the soil moisture deficit, $DF$ [L], is calculated by the relationship:

$$DF = T - I_t$$

(5.7)

and the runoff as

$$QP = I_1 - T$$

(5.8)

where $I_1$ is defined as $I_0 + P$, as presented schematically in Fig. 5.1.
Figure 5.1: Schematic definitions diagram of the API model.
CHAPTER 5. API-TYPE MODEL

Thus far, a linear relationship is assumed between rainfall, runoff and the infiltration, \( F \) [L]:

\[
F = P - QP \quad (5.9)
\]

The rainfall, runoff and initial abstraction relationships are presented schematically by line 'a' in Fig. 5.2. The actual data for four watersheds presented in Figs. 5.3 – 5.6 highlights the actual relationship between the rainfall and the observed runoff for four different watersheds in southern Arizona. It can be seen that the direct correlation between the two variables is quite poor and for prediction or forecasting procedures one should look for some parameters to improve it. From these figures and other observations it was realized that when using line 'a', the predicted runoff produced from small events is overestimated whereas from large runoff events it is underestimated. It was concluded that replacing line 'a' with linear line 'b' better represents the observed runoff. Following this idea Eq. 5.8 can be rewritten as

\[
QP = (I_1 - T) \cdot RF \quad (5.10)
\]

where \( RF \) is the reduction factor from the 1:1 line 'a' (Fig. 5.2).

Furthermore, it was also found (e.g. in the SCS model, Soil Conservation Service, 1972) that a nonlinear relationship between rainfall and runoff would fit even better. Consequently, another factor should be introduced into Eq. 5.10 which results in an equation of the form:

\[
QP = (I_1 - T) \cdot RF + (I_1 - T)^2 \cdot CF \quad (5.11)
\]

where \( CF \) is the curve factor. Now the relationship between the precipitation and the runoff is represented by line 'c' (Fig. 5.2).
Figure 5.2: Schematic presentation of possible rainfall – runoff relationships.
Figure 5.3: Rainfall — observed runoff relationships for Watershed 11.
Figure 5.4: Rainfall – observed runoff relationships for Lucky Hills 101.
Figure 5.5: Rainfall – observed runoff relationships for Santa Rita 1.
Figure 5.6: Rainfall – observed runoff relationships for Santa Rita 4.
CHAPTER 5. API-TYPE MODEL

5.3 Methods

The four-parameter multiplicative model, derived in the previous section (Eq. 5.11), was tested with data from four watersheds in southern Arizona:


2. Lucky Hills 101, located in the Walnut Gulch Experimental Watershed, 0.013 km\(^2\), sandy-loam, using seventeen years of data (1965 – 1981).

3. Santa Rita 1, a subwatershed in the Santa Rita Experimental Watershed, 0.02 km\(^2\), sandy, using eight years of data (1975 – 1982).

4. Santa Rita 4, a subwatershed in the Santa Rita Experimental Watershed, 0.02 km\(^2\), clayey, using eight years of data (1975 – 1982).

Some statistical values of the rainfall and observed runoff for these watersheds are presented in Table 5.1.

The simulation starts after a dry spell at the beginning of the summer rainy season, usually after more than 30 days without rain during May and June. After this dry period \( I_0 \) is assumed to be zero. The simulation was stopped at the end of the summer rainy season (at the end of September).

For watershed 11, the largest of the four watersheds, ten rain gages were used and the rainfall was averaged over the area by using the Thiessen weight method. For the other smaller watersheds the simulation was based on data from a single rain gage.
Table 5.1: Statistical characteristic of rainfall, observed and predicted runoff.

<table>
<thead>
<tr>
<th></th>
<th>Watershed 11</th>
<th>Lucky Hills 101</th>
<th>Santa Rita 1</th>
<th>Santa Rita 4</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Rainfall</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No. of observations</td>
<td>468</td>
<td>522</td>
<td>189</td>
<td>202</td>
</tr>
<tr>
<td>sample average (mm)</td>
<td>5.62</td>
<td>6.78</td>
<td>6.81</td>
<td>6.39</td>
</tr>
<tr>
<td>standard deviation</td>
<td>7.64</td>
<td>7.93</td>
<td>8.78</td>
<td>7.67</td>
</tr>
<tr>
<td>minimum value (mm)</td>
<td>0.01</td>
<td>0.25</td>
<td>0.30</td>
<td>0.25</td>
</tr>
<tr>
<td>maximum value (mm)</td>
<td>53.94</td>
<td>72.64</td>
<td>47.00</td>
<td>35.81</td>
</tr>
<tr>
<td><strong>Observed runoff</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No. of observations</td>
<td>100</td>
<td>111</td>
<td>58</td>
<td>84</td>
</tr>
<tr>
<td>sample average (mm)</td>
<td>0.24</td>
<td>0.72</td>
<td>0.61</td>
<td>1.10</td>
</tr>
<tr>
<td>standard deviation</td>
<td>1.06</td>
<td>2.95</td>
<td>1.87</td>
<td>2.63</td>
</tr>
<tr>
<td>minimum value (mm)</td>
<td>0.001</td>
<td>0.025</td>
<td>0.002</td>
<td>0.075</td>
</tr>
<tr>
<td>maximum value (mm)</td>
<td>15.63</td>
<td>45.16</td>
<td>13.73</td>
<td>17.30</td>
</tr>
<tr>
<td><strong>Predicted runoff</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No. of observations</td>
<td>143</td>
<td>128</td>
<td>62</td>
<td>95</td>
</tr>
<tr>
<td>sample average (mm)</td>
<td>0.24</td>
<td>1.00</td>
<td>0.58</td>
<td>0.92</td>
</tr>
<tr>
<td>standard deviation</td>
<td>0.87</td>
<td>2.68</td>
<td>1.46</td>
<td>1.82</td>
</tr>
<tr>
<td>minimum value (mm)</td>
<td>0.001</td>
<td>0.001</td>
<td>0.001</td>
<td>0.001</td>
</tr>
<tr>
<td>maximum value (mm)</td>
<td>10.132</td>
<td>43.05</td>
<td>12.64</td>
<td>9.41</td>
</tr>
</tbody>
</table>
CHAPTER 5. API-TYPE MODEL

The simulated values of the predicted runoff, \( Q_P \), have been compared against the observed runoff, \( Q_O \). The SIMPLEX optimization subroutine (Nelder and Mead, 1965) was used to find the minimum value between the predicted runoff and the observed runoff by calculating the least squares objective function (\( FUNC \)):

\[
FUNC = \sum_{i=1}^{n} (Q_P - Q_O)^2
\]  \hspace{1cm} (5.12)

where \( n \) is the number of days which have either observed or predicted runoff or both.

For the evaluation of the model two criteria were used: (1) the proportion of variability explained \( (r^2) \) between the \( Q_P \) and \( Q_O \); and (2) the standard error of estimate \( (SEE) \) calculated by:

\[
SEE = \sqrt{\frac{\sum_{i=1}^{N} (Q_P - Q_O)^2}{N - 2}}
\]  \hspace{1cm} (5.13)

where \( N \) is the total number of observations \( (N = 468 \) for Watershed 11, etc.).

5.4 Results

Table 5.2 summarizes the optimized parameters and the results between the observed and predicted runoff in terms of the proportion of variability explained \( (r^2) \) and the standard error of estimate \( (SEE) \). The correlations between the observed and predicted runoff based on rainfall events greater than the threshold parameter for each watershed are presented in Figs. 5.7 - 5.10. The highest correlation value \( (r^2 = 0.86) \) was obtained in Lucky Hills 101, whereas the worst correlation \( (r^2 = 0.62) \) was obtained in Watershed 11.
Figure 5.7: Correlation between observed and predicted runoff for Watershed 11.
Figure 5.8: Correlation between observed and predicted runoff for Lucky Hills 101.
Figure 5.9: Correlation between observed and predicted runoff for Santa Rita 1.
CHAPTER 5. API-TYPE MODEL

Figure 5.10: Correlation between observed and predicted runoff for Santa Rita 4.
probably because of the spatial distribution of the rainfall over the relative large watershed area.

Perhaps the most interesting parameter is the runoff threshold which is a function of the soil texture. Thus, the lowest threshold value ($T = 4.06\,mm$) is obtained for the clayey texture in Santa Rita 4, the highest value ($T = 9.00\,mm$) for the sandy texture in Santa Rita 1 and the medium values ($T = 6.83\,mm$ and $T = 5.70\,mm$) for the sandy-loam texture in Watershed 11 and Lucky Hills 101, respectively.

### 5.5 Connection between the API and Green and Ampt models

The 'difference in soil moisture across the wetting front' parameter in the Green and Ampt model, $M\, [L^3/L^3]$, is a function of the soil texture and the residual soil moisture:

$$M = \theta_s - \theta_i = 1 - S_e$$

where $\theta_s$ and $\theta_i$ are the saturation and initial soil moisture $[L^3/L^3]$, respectively, and the $S_e$ is the effective saturation. Theoretically the latter term, $S_e$, assumes a variation between zero, under very dry conditions, and one, under saturated conditions. Therefore, the effective saturation is the ratio between these extreme soil moisture conditions:

$$S_e = \frac{\theta_i}{\theta_s}$$

In the API-type model the soil moisture content, $I$, is equivalent to $\theta_i$ and the threshold, $T$, is equivalent to $\theta_s$. Therefore, the difference in soil moisture across the wetting front, $M$, can be rewritten as

$$M = \frac{DF}{T}$$
CHAPTER 5. API-TYPE MODEL

By introducing Eq. 5.7 into Eq. 5.16, the effective matric potential, $SM$, can be written as

$$SM = S_f \cdot n_e \cdot (1 - S_e) = \frac{S_f \cdot n_e \cdot (T - I_t)}{T}$$

(5.17)

where $S_f$ is the average potential across the wetting front and $n_e$ is the effective porosity.

Table 5.3 summarizes an example of the parameters' range for the various soil moisture conditions – saturation, field capacity, wilting point and maximum dry, for a sandy-loam soil.

5.6 Example

This section presents an example simulation of the API model for Watershed 11 for the year 1971 with the optimized parameters which are presented in Table 5.2. The year 1971 was chosen because it contained three events to be tested with CELLMOD. The simulation begins on the 24th of June after a dry spell of at least 66 days at each of the 10 rain gages of the watershed. The daily simulation steps, predicted and observed runoff as well as the errors are presented in Table 5.4 and illustrated in Fig. 5.11. It can be seen that the differences between the observed and predicted runoff are relatively small, consequently it is assumed that the model succeeds in performing good simulation of the seasonal variation of the soil moisture.

On August 12, 1971 ($ND = 224$) there were 20.332 mm of rainfall in Watershed 11. For this day Table 5.4 indicates $I_0 = 5.282$ mm (note that $I_t$ of $ND = 223$ is equal to $I_0$ of $ND = 224$). Solving Eq. 5.17 for the storm of Aug. 12, 1971, with average capillary potential data from Table 4.4 (the
### Table 5.2: Optimized parameters and summary of results for the API model.

<table>
<thead>
<tr>
<th>Watershed</th>
<th>T</th>
<th>K</th>
<th>RF</th>
<th>CF</th>
<th>QPmean</th>
<th>r^2</th>
<th>SEE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Watershed 11</td>
<td>6.83</td>
<td>0.25</td>
<td>-0.02</td>
<td>0.004</td>
<td>0.24</td>
<td>0.62</td>
<td>0.93</td>
</tr>
<tr>
<td>Lucky Hills 101</td>
<td>5.70</td>
<td>0.25</td>
<td>-0.03</td>
<td>0.010</td>
<td>0.74</td>
<td>0.86</td>
<td>1.45</td>
</tr>
<tr>
<td>Santa Rita 1</td>
<td>9.00</td>
<td>0.13</td>
<td>-0.02</td>
<td>0.006</td>
<td>0.92</td>
<td>0.77</td>
<td>1.25</td>
</tr>
<tr>
<td>Santa Rita 4</td>
<td>4.06</td>
<td>0.11</td>
<td>-0.02</td>
<td>0.005</td>
<td>0.91</td>
<td>0.66</td>
<td>1.36</td>
</tr>
</tbody>
</table>

### Table 5.3: Range of parameters for various soil moisture conditions for a sandy-loam soil.

<table>
<thead>
<tr>
<th></th>
<th>Saturation</th>
<th>Field Capacity</th>
<th>Wilting Point</th>
<th>Maximum Dry</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effective saturation, Se (%)</td>
<td>1.00</td>
<td>0.49</td>
<td>0.22</td>
<td>0.0</td>
</tr>
<tr>
<td>Soil Moisture deficit, DF (mm)</td>
<td>0.00</td>
<td>3.35</td>
<td>5.33</td>
<td>6.83</td>
</tr>
<tr>
<td>Difference in Average Soil Moisture, M (mm^3/mm^3)</td>
<td>0.00</td>
<td>0.51</td>
<td>0.78</td>
<td>1.00</td>
</tr>
<tr>
<td>Effective Matric Potential, SM (mm)</td>
<td>0.00</td>
<td>18.8</td>
<td>28.8</td>
<td>36.90</td>
</tr>
</tbody>
</table>
**CHAPTER 5. API-TYPE MODEL**

Table 5.4: Results of API model for Watershed 11, 1971.

- **OPTIMIZED PARAMETERS:**
  - OPTIMIZED THRESHOLD LEVEL = 6.83172
  - OPTIMIZED RECESSION FACTOR = 0.25701
  - OPTIMIZED REDUCTION FACTOR = -0.02056
  - OPTIMIZED CURVE FACTOR = 0.00405

<table>
<thead>
<tr>
<th>ND</th>
<th>INT</th>
<th>P  (mm)</th>
<th>QO (mm)</th>
<th>I1 (mm)</th>
<th>IT (mm)</th>
<th>QP (mm)</th>
<th>E   (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>175</td>
<td>8</td>
<td>5.974</td>
<td>0.000</td>
<td>5.974</td>
<td>0.764</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>183</td>
<td>1</td>
<td>1.306</td>
<td>0.000</td>
<td>2.070</td>
<td>1.601</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>184</td>
<td>7</td>
<td>0.479</td>
<td>0.000</td>
<td>2.080</td>
<td>0.344</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>191</td>
<td>6</td>
<td>0.092</td>
<td>0.000</td>
<td>0.436</td>
<td>0.093</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>197</td>
<td>1</td>
<td>2.163</td>
<td>0.000</td>
<td>2.256</td>
<td>1.745</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>198</td>
<td>1</td>
<td>0.752</td>
<td>0.000</td>
<td>2.497</td>
<td>1.931</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>199</td>
<td>1</td>
<td>5.542</td>
<td>0.000</td>
<td>6.831</td>
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<td>3.073</td>
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<td>0.419</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>261</td>
<td>11</td>
<td>22.528</td>
<td>0.883</td>
<td>8.172</td>
<td>0.404</td>
<td>1.342</td>
<td>0.459</td>
</tr>
</tbody>
</table>
Figure 5.11: Results of API model for Watershed 11, 1971.
texture in Watershed 11 is sandy–loam), gives

\[ SM = 90.0 \times 0.41(6.83 - 5.282)/6.83 = 8.376 \text{ mm} \]  \hspace{1cm} (5.18)

The use of the effective matric potential value will be demonstrated later in Chapter 7.

5.7 Conclusions

Although the API model is an old procedure among the rainfall–runoff models for predicting direct runoff, the derived API–type model described above appears to be a practical tool for estimating the initial moisture deficit prior to a selected day. This significant parameter in rainfall–runoff modeling is usually hard to measure or estimate.

The seasonal soil moisture variation is not estimated directly from the model but is concluded from fitting the predicted and the observed runoff with the optimization procedure.

The index is based only on the daily rainfall measurements which are often the only available data. The index does not rely on the soil characteristics although it was shown that the threshold parameter reflects the soil texture of the watershed.

The proposed index should be examined for more watersheds with different soil textures. When Table 5.4 is completed for all soil texture classes it can be a useful tool for parameter estimations for rainfall–runoff models.
Chapter 6

GEOGRAPHIC INFORMATION SYSTEM

6.1 Introduction

During the past decade, computerized Geographic Information Systems (GIS) have been designed to accept, organize, statistically analyze and/or display diverse types of data. Large volumes of spatial and temporal information are digitally referenced to a common coordinate system of a particular projection and scale. Each variable is archived in a computer-compatible digital format as a geographically referenced layer or plane called a data base. When the layers are digitally coregistered, the data set of n layers compose the GIS data bank related to a given problem (Avery and Berlin, 1985).

The GIS consists of three components: (1) positional or map data which are explicit locational identifiers such as Cartesian coordinates, associated with the spatial entities of points, lines, and areas or polygons; (2) attribute or descriptive data presents both qualitative data (e.g., soil series) and quantitative data (e.g., soil texture, soil conductivity or soil porosity) keyed
to each spatial entity; and (3) time – the attributes at a specific location can be monitored through time.

Because CELLMOD, the rainfall–runoff model, requires several variables and parameters, each with different spatial variability, the main task of the GIS used in conjunction with this project is to interrelate the required variables and parameters on a common base (scale and format). Using the overlay operation, the GIS makes it possible to operate the model incorporating any nonuniformity of the variables and parameters.

The GIS hardware and software used in this project is called ERDAS which is an integrated image processing and geographic information system, based on a PDP–11 mini–computer. The main hardware components are a high resolution (512x512x32 bit) true color display and a tablet digitizer.

6.2 GIS – subsystems

Five basic component subsystems are included in a typical GIS (Short, 1982):

1. Data input – the system information may be derived from a variety of sources such as analog maps, air photographs, digital satellite images, tabular data, graphic data or digital data. The data can be captured into the system either manually (e.g. via digitizer) or automatically (e.g. via scanner).

2. Encoding – spatial data which relate to the land and are encoded with relation to location are called geo–referenced or geo–coded data. These have three most common topological formats – points (nodes), lines (arcs or links) and polygons. They can be used in two–position indexing systems: (1) grid–cell or raster coding system which consists
of a systematic array of squares superimposed over the terrain; and
(2) a polygon or vector coding system in which the perimeter of each
areal unit containing the desired attribute data is digitally encoded
and stored.

3. Data management – after the spatial data have been encoded, they
are stored in the data bank. Each variable (called also a GIS layer
or file) is archived in a computer–compatible digital format as a geo-
graphically referenced plane. When the layers are digitally registered
to one another, they form a GIS data base composed of \( n \) layers. The
data management element consists of a series of computer programs
to perform all data entry, storage, retrieval and maintenance tasks.

4. Data manipulation and analysis – data manipulation refers to opera-
tions done on the data in order to make them more suitable for future
processing. Two types of automated analysis can be performed. The
first is surface analysis which applies to intravariable relationships
within the data set, such as grouping categories, statistical analyses,
area measurement and labeling and the second is overlay analysis of
two or more data layers.

5. Output products – the output products of the GIS can be in the form
of written reports, tables, graphic displays on a monitor, maps, or
statistical summaries.

6.3 Data input

This study involves numerous GIS files (layers) which have been created
from several types of data sources (Table 6.1). As discussed in Chapter 3,
Table 6.1: GIS layers and data sources.

<table>
<thead>
<tr>
<th>GIS LAYER</th>
<th>DATA SOURCE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Model cells</td>
<td>Topographic maps and aerial photographs</td>
</tr>
<tr>
<td>2. Rainfall intensity</td>
<td>Rain gage stations</td>
</tr>
<tr>
<td>3. Rainfall intensity</td>
<td>Weather radar</td>
</tr>
<tr>
<td>4. Field hydraulic conductivity</td>
<td>Field soil survey</td>
</tr>
<tr>
<td>5. Rock content</td>
<td>Field soil survey</td>
</tr>
<tr>
<td>6. Bulk density</td>
<td>Field soil survey</td>
</tr>
<tr>
<td>7. Effective porosity</td>
<td>Field soil survey</td>
</tr>
<tr>
<td>8. Average potential</td>
<td>Field soil survey</td>
</tr>
<tr>
<td>9. Average matric potential</td>
<td>Field soil survey</td>
</tr>
<tr>
<td>10. Vegetation cover</td>
<td>Aerial photographs</td>
</tr>
<tr>
<td>11. Ground cover</td>
<td>Ground level photographs</td>
</tr>
<tr>
<td>12. Soil moisture</td>
<td>Rain gages / weather radar</td>
</tr>
</tbody>
</table>
the semi-distributed model consists of a system of tree-like interconnected cells, each representing a certain portion of the watershed. The model cells are the basic structure of the semi-distributed model because by performing the routing computation for each cell in a sequence it is possible to derive a surface runoff hydrograph.

The size of the model cells is a function of the drainage pattern and the watershed terrain (Fig. 6.1). The cells are obtained from topographic maps and aerial photographs. The 35 cells in Fig. 6.1 were digitized for the GIS file from a topographic map. Generally, each cell boundary starts near the intersection of two streams and from this point follows the dividing line between adjacent watersheds.

The rainfall intensity cells may cover the watershed area in two forms: Thiessen polygons and ground based meteorological radar pixels. The Thiessen method is an interpolation technique in which the estimated value at any given point (of rainfall intensity in this case) is taken as the observed value at the nearest station (rain gage). Consequently, the number of polygons is the same as the number of the rain gage stations. The 17 Thiessen polygon boundaries were calculated by the method described in Chow (1964) and Linsley et al. (1982) and were hand-traced on a digitizer into the GIS file (Fig. 6.2).

The spatial node locations (X,Y coordinates) of the radar pixels were obtained by trigonometrical calculations, based on the knowledge of the radar site, and the width resolution and range resolution of the radar beam. The four X,Y coordinates of each pixel were manually entered into the GIS file from tabulated data. The connecting lines between four nodes form the radar pixel. The study area is covered by 22 radar pixels.
Figure 6.1: Model cells in Watersheds 8 and 11.
Figure 6.2: Thiessen polygons in Watersheds 8 and 11.
Seven different soil series have been defined by the SCS soil survey at the study area. The survey results, drawn on large scale (1:12,000) aerial photographs, provide the data source and the base map for the soil characteristics involved in the rainfall–runoff model. The quantitative GIS layers include the following attributes: field saturated hydraulic conductivity, rock content, bulk density, effective porosity, average potential and average matric potential, all of which are based on the soil series boundaries digitized into the GIS file (Fig. 6.3).

The vegetation cover file was created by interpretation of low altitude aerial photographs (Chapter 4). The values of vegetation cover from the pictures were area–weighted averaged in order to create one vegetation cover value for each Thiessen polygon covering the same area as the pictures.

The ground cover file was created by interpretation of ground–level photographs (Chapter 4). The ground cover values were assigned to the soil series polygons.

Soil moisture is a unique attribute because it has both spatial and temporal variability. As pointed out earlier (Chapter 5), for a forecasting model, it is extremely important to know the soil moisture deficit at the beginning of each storm. The soil moisture deficit values are estimated, in the API–type procedure, for each Thiessen polygon from daily rainfall data. Consequently, the GIS file should be updated every day.

6.4 Data encoding

All the GIS files of the present study were stored in a topological format based on the Universal Transverse Mercator projection (UTM). The large
Figure 6.3: Soil series polygons in Watersheds 8 and 11.
scale aerial photographs had been geometrically corrected and scaled in order to be registered with the other topographic maps. The rain gage file was stored in point (node) format, the streams and the topography files in line (link) format and all the other files in polygon format.

6.5 Data management

The polygon format files were converted to grid-cell format files. Each grid-cell is assigned a single value of the variable/parameter of the data file. The grid format is the most popular data structure because it is a relatively simple way to organize data, it is efficient and inexpensive to store, operate and analyze and can be of any dimension (Curran, 1985; Dangermond, 1983). In the current study each GIS layer consists of 256 rows and 512 columns which create 131,072 grid-cells. Each grid-cell covers 670 m².

6.6 Data manipulation

As mentioned previously in this chapter, the rainfall-runoff model consists of several attributes (variables and parameters), each of which has spatial variability. Thus, the main objective of the GIS operation in conjunction with the current model is to produce new data sets which take into consideration the combined spatial variability of the attributes. This operation is involved in interrelating the polygon nets throughout the watershed to calculate different combinations of GIS layers for the purpose of area measurement.

The grid-cell overlay method (Jensen, 1986) was used to generate the composite maps (multiple layer maps) which contain new polygons and
result in numerical weighting factors for the new composite data set. For example, overlaying \( n \) polygons by \( m \) polygons creates a matrix of \( n \cdot m \) possibilities. If the overlapping polygons have a common area the matrix value will be greater than zero.

Fig. 6.4 summarizes the GIS structure in connection with the model computations. The data source includes the topographic map, aerial photographs, ground-level photographs, the soil survey map, rainfall data and, as an option, weather radar data. Seven GIS layers have been created from the above data sources. They are grouped in three different polygon forms: (1) the soil map that contains all the attributes related to the soil series such as the field hydraulic saturated conductivity, effective porosity, average potential, and the ground cover; (2) the Thiessen polygon map contains the rainfall intensity, soil moisture and canopy cover; and (3) the model cells map that is the base map of the rainfall–runoff model.

The computation of the rainfall excess is performed for each Thiessen polygon (Chapter 3), however the attributes for the Green and Ampt equation have the same spatial variability as the soil series. Therefore, the Thiessen polygon map was overlaid by the soil map and each attribute was multiplied by the resulting weighting factor. For example, the percentage of ground cover observed for each soil series is multiplied by the weighting factor resulting in the percentage of ground cover in each Thiessen polygon. The same procedure is used to assign the rainfall excess values to each individual model cell. The weighting factors were computed by overlaying the Thiessen polygon map over the model cells map.
CHAPTER 6. GEOGRAPHIC INFORMATION SYSTEM

Figure 6.4: Schematic diagram of the GIS.
6.7 Output products

Two types of output products of the grid–cell overlay operation have been created: map plots and tabular summaries (matrix tables). Figs. 6.5 and 6.6 show, respectively, the soil series map superimposed on the Thiessen polygon map and the Thiessen polygon map superimposed on the model cells map. Table 6.2 presents the overlay matrix of the 7 soil polygons and the 17 Thiessen polygons. Table 6.3 presents the weighting factors for this case. The sum of weights for each Thiessen polygon is equal to unity. It can be seen, for example, that the area of Thiessen polygon 1 covers 55% of soil polygon 1, 24.1% of soil polygon 4 and of 20.9% soil polygon 6. The percentage of ground cover in Thiessen polygon 1 is calculated by summing the products of the percentage of ground cover in each soil polygon and the respective weighting factor:

$$12.825 \times 0.55 + 36.66 \times 0.241 + 35.247 \times 0.209 = 23.265\%$$

Since the entire study area consists of only one soil texture (sandy–loam), the effective porosity and the average potential have no spatial variability and a single value was used for each of these parameters. If the rainfall intensity is obtained by weather radar, all the soil polygon values are assigned to the radar pixels rather than to the Thiessen polygons.

Tables 6.4 and 6.5 present a similar procedure for overlaying the Thiessen polygons and the model cells. In addition, the bottom line in Table 6.5 presents the weighting factors for calculating the average precipitation for the entire area. These tables consist of only 31 model cells because 4 cells (numbers 32 to 35) are located above stock ponds (Fig. 6.1) and rarely contribute runoff to the downstream cells.
Figure 6.5: Soil map overlaid by Thiessen polygons (Figs. 6.2 and 6.3).
Figure 6.6: Thiessen polygons overlaid by model cells (Figs. 6.1 and 6.2).
Table 6.2: Overlay matrix for soil polygons and Thiessen polygons.

<table>
<thead>
<tr>
<th>Thiessen Polygons No.</th>
<th>Area (sq. km.)</th>
<th>Soil Polygon No.</th>
<th>Overlay Matrix</th>
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<td>0.252</td>
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<td>0.174</td>
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<td>0.174</td>
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<tr>
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<td>17</td>
<td>0.823</td>
<td></td>
<td>0.056</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Area of Soil Polygon (sq. km.)</td>
<td>5.399</td>
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</table>
### Table 6.3: Weighting factors for overlaying soil polygons and Thiessen polygons.

<table>
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<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area (sq.km.)</td>
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<td>0.383</td>
<td>3.107</td>
<td>0.206</td>
<td>0.030</td>
<td>0.773</td>
<td>4.804</td>
</tr>
<tr>
<td>GC in Soil Polygons (%)</td>
<td>2.825</td>
<td>9.221</td>
<td>28.001</td>
<td>36.660</td>
<td>37.003</td>
<td>35.247</td>
<td>44.375</td>
</tr>
<tr>
<td>Ksbar in S. P. (mm/hr)</td>
<td>15.000</td>
<td>17.000</td>
<td>16.000</td>
<td>16.000</td>
<td>16.000</td>
<td>19.000</td>
<td>17.000</td>
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</table>

<table>
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<tr>
<th>Thiessen Polygons</th>
<th>No.</th>
<th>Area (sq.km.)</th>
<th>Weighting Factors</th>
<th>Thiessen Poly.</th>
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<td>0.241</td>
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<td>0.403</td>
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<td>0.795</td>
<td>0.899</td>
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Table 6.5: Weighting factors for overlaying Thiessen polygons and model cells.

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| Weighting Factors | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 |
|-------------------|---|---|---|---|---|---|---|---|---|----|----|----|----|----|----|----|----|---|
| .506              | .704|   |   |   |   |   |   |   |   | .296|   |   |   |   |   |   |   |
| .402              | .506|   |   |   |   |   |   |   |   | .125| .368|   |   |   |   |   |   |
| .640              |   | .030|   | .704|   |   | .266|   |   |   |   |   |   |   |   |   |   |
| .387              |   |   | .769|   |   | .026| .205|   |   |   |   |   |   |   |   |   |   |
| .627              |   |   |   | .475| .525|   |   |   |   |   |   |   |   |   |   |   |   |
| .299              |   |   |   |   | .201|   | .799|   |   |   |   |   |   |   |   |   |   |
| .261              |   |   |   | .452|   | .548|   |   |   |   |   |   |   |   |   |   |   |
| .281              |   |   |   | .079| .921|   |   |   |   |   |   |   |   |   |   |   |   |
| .346              |   |   | .805|   | .195|   |   |   |   |   |   |   |   |   |   |   |   |
| .498              |   |   |   | .114| .623| .263|   |   |   |   |   |   |   |   |   |   |   |
| .589              |   | .833|   | .114| .052|   |   |   |   |   |   |   |   |   |   |   |   |
| .619              | .093| .073| .530|   | .052|   |   |   |   |   |   |   |   |   |   |   |   |
| .719              | .635| .365|   | .003|   |   |   |   |   |   |   |   |   |   |   |   |   |
| .400              | .243| .755|   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |
| .473              | .882| .019|   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |
| .138              | .580|   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |
| .248              |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |
| .155              |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |
| .381              | .367| .633|   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |
| .433              | .139| .032| .166| .005|   | .658|   |   |   |   |   |   |   |   |   |   |   |
| .419              | .702| .298|   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |
| .261              |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |
| .531              | .359| .618| .004|   |   |   |   |   |   |   |   |   |   |   |   |   |   |
| .684              | .246| .297|   |   | .458|   |   |   |   |   |   |   |   |   |   |   |   |
| .749              | .991| .008| .001|   |   |   |   |   |   |   |   |   |   |   |   |   |   |
| .493              | .441| .559|   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |
| .281              | .521| .479|   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |
| .508              | .036| .453|   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |
| .291              |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |
| .364              | .692| .184|   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |

|               | .511|   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |
|               | .124|   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |

CHAPTER 6. GEOGRAPHIC INFORMATION SYSTEM

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6.8 Conclusions

The Geographic Information System is used for several purposes such as map scaling and geometrical correction of aerial photographs. The most useful feature of the GIS in conjunction with the current study is its ability to coregister variables and parameters one to another on a common base by using the grid–cell operation. This feature of the GIS enables the user to operate the model incorporating nonuniformity of the model variables and parameters.

It can be concluded that the GIS plays an important role in a semi-distributed rainfall–runoff model. However, probably one of the biggest challenges is to integrate a GIS as a part of a big and complex model.
Chapter 7

MODEL OPERATION

7.1 Introduction

Before using CELLMOD it is necessary to compute the API model in order to obtain the initial soil moisture deficit for the event under consideration. The operation of the API model was presented in Chapter 5. This chapter defines the input data required for the main routine, discusses model performance, and presents model output. The model operation is demonstrated using the rainfall–runoff event which occurred on August 12, 1971 (6) in Watershed 11, at the Walnut Gulch Experimental Watershed. This was the sixth event (out of 21) with available data for calibrating and testing the model.

7.2 The study area

The watershed chosen for this project is the Walnut Gulch Experimental Watershed, operated by the Agricultural Research Service of the United State Department of Agriculture (USDA–ARS) located about 100 km southeast of Tucson (Fig 7.1). The watershed is representative of the semi-
Figure 7.1: Location map.

Elevations on the watershed range from 1,280 meters to 1,830 meters (MSL). The watershed dissect a high foothill alluvial fan with soil texture material ranging from clays and silts to well–cemented boulder conglomerates. The climax vegetation of the Walnut Gulch area is desert plain grassland. About 60 percent of the watershed supports desert shrubs and 40 percent is grass–covered with few scattered shrubs.

The annual mean precipitation in this area is about 300 mm. The precipitation distribution is bimodal with slow moving cold fronts providing lift for winter precipitation and convective heating of moist tropical air producing summer rainfall. Nearly all the streamflow occurs between July and early October and results from intense, convective thunderstorms of short duration and limited areal extent. During an average year, five to ten individual runoff events are recorded at the gaging stations with the channel being dry about 99 percent of the time.

The 150 km$^2$ watershed is divided into 12 gaged subdrainages of various sizes ranging upward from 2 km$^2$ to the entire watershed. The watershed is equipped with a network (1.6x1.6 km grid) of 95, 24–hr weighing–type recording rain gages in continuous operation since 1956.

The study is limited to two subwatersheds: Watershed 8 (14.70 km$^2$) and Watershed 11 (6.28 km$^2$) (Fig. 7.1). Watershed 8 includes Watershed 11 in its area, thus runoff from the latter flows into the former watershed. Watershed 8 is covered by 17 rain gage stations (10 in Watershed 11 alone).

Approximately 30 percent of the two watersheds area is dominated by desert shrubs with a crown cover of approximately 30 percent and an un-
derstory of grasses with a basal area of less than 1 percent. Five soil series have been defined by the soil survey which was conducted by the SCS in 1986. All of them are sandy-loam in texture.

7.3 CELLMOD – data input

7.3.1 General

The input to the program consists of two main parts. The first part contains all the required watershed information which does not change with time. Therefore, this part is common to all events that occur in the same area. The second part contains all the specific event information including the initial soil moisture deficit, rainfall and runoff data.

7.3.2 Watershed information

The watershed information part includes the following sections:

Watershed identification

This section includes a character title for identifying the watershed or the project (Table 7.1).

<table>
<thead>
<tr>
<th>Table 7.1: CELLMOD watershed identification output.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Program CELLMOD output for:</td>
</tr>
<tr>
<td>-----------------------------------------------------</td>
</tr>
<tr>
<td>Walnut Gulch - Watershed no. 11</td>
</tr>
</tbody>
</table>
CHAPTER 7. MODEL OPERATION

Watershed characteristics

This section includes general information about the watershed consisting of its area in \( km^2 \), the length of the main stream in \( km \), and the time increment used for computation throughout the program and for presentation of the results. The time increment is expressed in hours but an option exists to express the time unit in minutes. The characteristics of Watershed 11 are presented in Table 7.2.

Table 7.2: Watershed 11 characteristics.

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Watershed area</td>
<td>6.280 sq.km.</td>
</tr>
<tr>
<td>Stream length</td>
<td>12.829 km.</td>
</tr>
<tr>
<td>Time increment</td>
<td>0.050 hr.</td>
</tr>
</tbody>
</table>

Cell model structure

This section of the input contains general information consisting of the number of cells in the model. Watershed 11 has been divided into 14 cells. In addition to the number of model cells, an area indicator and a stream length indicator can be specified (Table 7.3). If the area indicator or the stream length indicator is zero, no information will be available about the size or stream length of individual cells, and the program will assign equal area or equal stream length to all cells. Otherwise, the area, channel length and the average channel width of each cell should be specified.

To ensure the correct sequence of computations the cells have been given identification numbers such that the lower numbers are given to the upstream cells and the higher numbers to cells located downstream. All the
Table 7.3: Model cells characteristics and structure.

<table>
<thead>
<tr>
<th>IC</th>
<th>ID</th>
<th>Upstream Cells</th>
<th>AC</th>
<th>LC</th>
<th>WC</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3</td>
<td>0 0 0 0 0</td>
<td>0.504</td>
<td>1.536</td>
<td>5.0</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>0 0 0 0 0</td>
<td>0.402</td>
<td>0.976</td>
<td>5.0</td>
</tr>
<tr>
<td>3</td>
<td>4</td>
<td>1 1 0 0 0</td>
<td>0.402</td>
<td>1.024</td>
<td>5.0</td>
</tr>
<tr>
<td>4</td>
<td>7</td>
<td>3 3 0 0 0</td>
<td>0.387</td>
<td>1.000</td>
<td>12.0</td>
</tr>
<tr>
<td>5</td>
<td>6</td>
<td>0 0 0 0 0</td>
<td>0.627</td>
<td>1.122</td>
<td>5.0</td>
</tr>
<tr>
<td>6</td>
<td>7</td>
<td>5 5 0 0 0</td>
<td>0.299</td>
<td>0.854</td>
<td>6.0</td>
</tr>
<tr>
<td>7</td>
<td>14</td>
<td>4 6 0 0 0</td>
<td>0.261</td>
<td>0.634</td>
<td>12.0</td>
</tr>
<tr>
<td>8</td>
<td>9</td>
<td>0 0 0 0 0</td>
<td>0.281</td>
<td>0.902</td>
<td>3.0</td>
</tr>
<tr>
<td>9</td>
<td>10</td>
<td>8 8 0 0 0</td>
<td>0.346</td>
<td>0.829</td>
<td>3.0</td>
</tr>
<tr>
<td>10</td>
<td>11</td>
<td>9 9 0 0 0</td>
<td>0.498</td>
<td>0.537</td>
<td>5.0</td>
</tr>
<tr>
<td>11</td>
<td>12</td>
<td>10 10 0 0 0</td>
<td>0.589</td>
<td>1.024</td>
<td>5.0</td>
</tr>
<tr>
<td>12</td>
<td>13</td>
<td>11 11 0 0 0</td>
<td>0.619</td>
<td>1.049</td>
<td>5.0</td>
</tr>
<tr>
<td>13</td>
<td>14</td>
<td>12 12 0 0 0</td>
<td>0.719</td>
<td>0.976</td>
<td>6.0</td>
</tr>
<tr>
<td>14</td>
<td>15</td>
<td>7 13 0 0 0</td>
<td>0.104</td>
<td>0.268</td>
<td>12.0</td>
</tr>
</tbody>
</table>

**IC** = Identifying number of cell.  
**ID** = Identifying number of cell downstream.  
**AC** = Area of individual cell in sq. km.  
**LC** = Length of stream in an individual cell in km.  
**WC** = Average width of individual channel in m.  

Number of cells: 14  
Area indicator: 1  
Stream indicator: 1
cells delivering their output to a given interior cell should have identifying numbers lower than that of the cell considered.

The cell structure of Watershed 11 which is given in Table 7.3 has the same information as in Fig. 6.1. $IC$ is the identifying number of all the model cells and $ID$ is the identifying number of the downstream cell. Also included in the table are the identifying numbers of the cells located immediately upstream of the cell considered. Up to four such upstream cells can be specified for each interior cell in the model but this number can be changed by modifying the statement format.

**Output printing indicators**

A set of values for an indicator is used to activate various printing and plotting options. One value of this indicator is required for each cell. The values are read in the order of increasing cell identification numbers. The meanings assigned to the values of these indicators are according to the following code:

$IPT = 0$ – no printing or plotting of cell output data is required.

$IPT = 1$ – printing only the cell output data is required.

$IPT = 2$ – printing and plotting of cell output data is required.

$IPT = 3$ – printing and plotting of cell output data is required, as well as comparison to available measured data for the location of the outlet of the cell concerned.

In Table 7.4, printing indicator number 3 is specified for cell number 14. This cell is located near the Watershed 11 outlet and data from the flume is available for comparison with the model performance.
Number of rain gages and loss parameter indicators

Information given in this section (Table 7.5) includes the number of rain gages for which rainfall information is available as well as indicators for the availability of the infiltration and of the channel loss parameters. Zero values for either or both of these indicators signify that the corresponding parameters are not available. In this case the program assumes that the missing parameters are zero. A zero value for the infiltration parameters also means that the available rainfall data are the rainfall excess values.

Model parameters

There are three groups of the model parameters: (1) the infiltration parameters; (2) the routing parameters; and (3) the channel loss parameters.

1. Infiltration parameters – If the infiltration indicator is not zero, two operative parameters are involved in the rainfall excess calculations from the Green and Ampt infiltration equation – the saturated hydraulic conductivity, $K_\text{s}$, and the effective matric potential, $SM$, (Chapter 4). However these two parameters are the result of some previous calculations involving other parameters as illustrated in Fig. 7.2. The input for the model in this stage includes only the parameters which are related to the soil characteristics of the watershed and therefore are constant for all the storm events:

- $K_{\text{s,bar}}(j) =$ the saturated hydraulic conductivity for bare soil, in $mm/hr$.
- $CC(j) =$ canopy cover in percent.
- $CG(j) =$ ground cover in percent.
- $S_f(j) =$ the average potential in $mm$. 
Table 7.4: Output printing indicators.

<table>
<thead>
<tr>
<th>IC</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
<th>13</th>
<th>14</th>
</tr>
</thead>
<tbody>
<tr>
<td>IPT</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>3</td>
</tr>
</tbody>
</table>

IC — Identifying number of cell.
IPT — Output indicator.

Cells Where Output is Required:

0 — No printing is required.
1 — Print only cell output data.
2 — Print and plot cell output data.
3 — Print and plot cell output data and compare to observed.

Table 7.5: Number of rain gages and loss parameters indicators.

<table>
<thead>
<tr>
<th>Number of rain gages</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Infiltration parameters indicator</td>
<td>1</td>
</tr>
<tr>
<td>Channel loss parameters indicator</td>
<td>1</td>
</tr>
</tbody>
</table>
Figure 7.2: Structure of the model parameters estimation.
$n_e(j) = \text{the effective porosity in percent.}$

Table 7.6 presents the above parameters for each Thiessen polygon, $j$, represented by a rain gage. Note that because only one soil texture has been defined in Watershed 11 (sandy-loam), $S_f$ and $n_e$ have the same value for all the polygons.

The calculation of the difference in the average soil moisture across the wetting front, $M$, is done in the API model and out of the main routine. This parameter is calculated separately for each storm event as will be explained in a later section.

2. Routing parameters – Three parameters are involved in the routing operation, one of them in the surface runoff routing and the other two in the channel routing. The conversion of rainfall excess to surface outflow routing was explained in Chapter 3. The storage coefficient, $AKC$, for one linear reservoir is used to convert the rainfall excess into surface runoff (Table 7.7).

The other two parameters are used to convert channel inflow into channel outflow (Chapter 3). The parameter $TKF$ is the storage coefficient for a linear reservoir used for channel routing and the parameter $TDF$ is the time shift applied for the routed hydrograph. Both parameters are for a cell with average cell length and are expressed in hours. The values of these parameters for each cell are computed from the values read in proportion to the stream length in each cell relative to the average cell stream length (Table 7.7).

3. Channel loss parameters – Values of these parameters are required if the channel loss indicator is not zero. The first parameter, $CL(k)$, is
Table 7.6: Saturated hydraulic conductivity parameters and capillary potential parameters.

<table>
<thead>
<tr>
<th>ng</th>
<th>Ksbar</th>
<th>CC</th>
<th>GC</th>
<th>Sf</th>
<th>ne</th>
</tr>
</thead>
<tbody>
<tr>
<td>44</td>
<td>15.406</td>
<td>20.30</td>
<td>16.70</td>
<td>90.0</td>
<td>0.41</td>
</tr>
<tr>
<td>51</td>
<td>15.685</td>
<td>15.50</td>
<td>23.50</td>
<td>90.0</td>
<td>0.41</td>
</tr>
<tr>
<td>52</td>
<td>15.269</td>
<td>13.20</td>
<td>17.20</td>
<td>90.0</td>
<td>0.41</td>
</tr>
<tr>
<td>54</td>
<td>16.956</td>
<td>27.20</td>
<td>43.50</td>
<td>90.0</td>
<td>0.41</td>
</tr>
<tr>
<td>55</td>
<td>17.000</td>
<td>6.00</td>
<td>44.40</td>
<td>90.0</td>
<td>0.41</td>
</tr>
<tr>
<td>56</td>
<td>16.215</td>
<td>7.20</td>
<td>31.70</td>
<td>90.0</td>
<td>0.41</td>
</tr>
<tr>
<td>88</td>
<td>16.696</td>
<td>14.60</td>
<td>39.50</td>
<td>90.0</td>
<td>0.41</td>
</tr>
<tr>
<td>89</td>
<td>16.941</td>
<td>22.20</td>
<td>43.40</td>
<td>90.0</td>
<td>0.41</td>
</tr>
<tr>
<td>90</td>
<td>15.945</td>
<td>14.60</td>
<td>27.60</td>
<td>90.0</td>
<td>0.41</td>
</tr>
<tr>
<td>91</td>
<td>16.932</td>
<td>7.50</td>
<td>43.30</td>
<td>90.0</td>
<td>0.41</td>
</tr>
</tbody>
</table>

ng = Field number of rain gage.
Ksbar = Saturated conductivity for bare soil in mm/hr.
CC = Canopy cover in percent.
GC = Ground cover in percent.
Sf = Average potential in mm.
ne = Effective porosity in percent.
the constant channel loss parameter for each channel reach within the cell $k$, expressed in $mm/hr$. This parameter will be converted later in the program operation to $m^3/s$ as a function of the channel length and average width of each cell (Table 7.8).

The second parameter, $PLS$, is a dimensionless positive multiplier ($PLS < 1.0$) used to compute the initial rate of channel loss in addition to the constant rate derived from the first parameter $CL(j)$. The value of the initial channel loss is computed as a product of this parameter ($PLS$) and the peak flow minus the constant loss rate (Table 7.8).

The third parameter, $QKS$, is also a dimensionless positive multiplier ($QKS < 1.0$) used to compute the decrease in the additional channel loss per unit time. The additional channel loss at any time is computed as a product of this parameter and the value of the additional channel loss one time increment earlier (Table 7.8).

### 7.3.3 Storm information

This part of the input data contains information of a specific storm event and includes the following information:

**Storm identification**

Table 7.9 includes a character title for identifying the storm event and a storm zero time value. The zero time is the earliest time in hours and minutes when the rainfall began in one of rain gages. It is used as a common start time for all the rainfall and runoff computations.
Table 7.7: Routing parameters.

Surface storage coefficient, AKC = 0.27 hr.
Channel storage coefficient, TKF = 0.10 hr.
Time delay factor, TDF = 0.03 hr.

Table 7.8: Channel loss parameters.

IC = identifying number of cell
CL = constant channel loss in mm/hr.

<table>
<thead>
<tr>
<th>IC</th>
<th>CL</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>26.00</td>
</tr>
<tr>
<td>2</td>
<td>26.00</td>
</tr>
<tr>
<td>3</td>
<td>26.00</td>
</tr>
<tr>
<td>4</td>
<td>26.00</td>
</tr>
<tr>
<td>5</td>
<td>26.00</td>
</tr>
<tr>
<td>6</td>
<td>26.00</td>
</tr>
<tr>
<td>7</td>
<td>26.00</td>
</tr>
<tr>
<td>8</td>
<td>26.00</td>
</tr>
<tr>
<td>9</td>
<td>26.00</td>
</tr>
<tr>
<td>10</td>
<td>26.00</td>
</tr>
<tr>
<td>11</td>
<td>26.00</td>
</tr>
<tr>
<td>12</td>
<td>26.00</td>
</tr>
<tr>
<td>13</td>
<td>26.00</td>
</tr>
<tr>
<td>14</td>
<td>26.00</td>
</tr>
</tbody>
</table>

Initial loss ratio, PLS = 0.100
Loss decay factor, QKS = 0.850

Table 7.9: Storm identification and zero time.

710812 Walnut Gulch, Watershed 11, Storm of 12 Aug. 1971 (6)

Zero time = 21:13
CHAPTER 7. MODEL OPERATION

Difference in average soil moisture

The initial soil moisture deficit is computed for each polygon in the API model (Chapter 5) and its values transferred to the main program as the difference in soil moisture across the wetting front values, \( M(j) \), (Table 7.10). Data are for the storm of August 12, 1971 (6).

Number of rainfall increments and rainfall data

Table 7.11 presents the number of time intervals for which rainfall data are available for each rain gage. The number is based on the common zero time and covers the entire time period to the end of rainfall at that rain gage. The number of rain increments is followed by a set of rainfall intensities, \( P(k,i) \), for that rain gage \( (k) \) and for each time interval \( (i) \). The values given are mean rainfall intensity for the specified time interval in units of \( mm/hr \) and the set may include zero values for some or all time intervals.

In addition Table 7.11 presents the rates of rainfall for 10 rain gages of Watershed 11 for the storm of August 12, 1971 (6).

Number of available observed runoff ordinates

Table 7.12 presents the number of time intervals for available measured runoff data. The numbers are based on the common zero time and each number covers the entire time period to the end of runoff at the flow gaging station coinciding with the outlet of the cell concerned. If no runoff data are available for any cell a zero value is given for that cell. The numbers in the set are presented in the order of increasing cell identification numbers. If no measured runoff data are available for all cells, so that all values of output printing indicator (Table 7.4) are less than 3, then the set of the
Table 7.10: Difference in average soil moisture, for the storm of Aug. 12, 1971 (6).

ng  =  Field number of rain gage.
M   =  Difference in average soil moisture in mm.

<table>
<thead>
<tr>
<th>ng</th>
<th>M</th>
</tr>
</thead>
<tbody>
<tr>
<td>44</td>
<td>12.382</td>
</tr>
<tr>
<td>51</td>
<td>8.162</td>
</tr>
<tr>
<td>52</td>
<td>8.162</td>
</tr>
<tr>
<td>54</td>
<td>8.162</td>
</tr>
<tr>
<td>55</td>
<td>8.162</td>
</tr>
<tr>
<td>56</td>
<td>8.162</td>
</tr>
<tr>
<td>88</td>
<td>8.162</td>
</tr>
<tr>
<td>89</td>
<td>8.162</td>
</tr>
<tr>
<td>90</td>
<td>8.162</td>
</tr>
<tr>
<td>91</td>
<td>8.162</td>
</tr>
</tbody>
</table>
Table 7.11: Rainfall data for the storm of Aug. 12, 1971 (6).

T - Time in hours.
ng - Field number of rain gage.
NRG - Number of rainfall increments.

<table>
<thead>
<tr>
<th>T</th>
<th>ng 44</th>
<th>ng 51</th>
<th>ng 52</th>
<th>ng 54</th>
<th>ng 55</th>
<th>ng 56</th>
<th>ng 88</th>
<th>ng 89</th>
<th>ng 90</th>
<th>ng 91</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.05</td>
<td>2.540</td>
<td>2.032</td>
<td>1.270</td>
<td>5.080</td>
<td>0.000</td>
<td>4.826</td>
<td>2.032</td>
<td>93.218</td>
<td>2.032</td>
<td>0.000</td>
</tr>
<tr>
<td>0.10</td>
<td>2.540</td>
<td>2.032</td>
<td>1.270</td>
<td>5.240</td>
<td>11.007</td>
<td>4.826</td>
<td>76.877</td>
<td>93.218</td>
<td>2.032</td>
<td>0.000</td>
</tr>
<tr>
<td>0.15</td>
<td>2.540</td>
<td>25.315</td>
<td>1.270</td>
<td>60.960</td>
<td>33.020</td>
<td>4.826</td>
<td>87.037</td>
<td>93.218</td>
<td>2.032</td>
<td>0.000</td>
</tr>
<tr>
<td>0.20</td>
<td>2.540</td>
<td>71.882</td>
<td>68.580</td>
<td>83.820</td>
<td>48.429</td>
<td>4.826</td>
<td>87.037</td>
<td>93.218</td>
<td>25.908</td>
<td>0.000</td>
</tr>
<tr>
<td>0.25</td>
<td>32.173</td>
<td>71.882</td>
<td>68.580</td>
<td>83.820</td>
<td>79.248</td>
<td>33.613</td>
<td>32.512</td>
<td>34.036</td>
<td>73.660</td>
<td>57.658</td>
</tr>
<tr>
<td>0.30</td>
<td>91.440</td>
<td>39.624</td>
<td>68.580</td>
<td>48.260</td>
<td>35.391</td>
<td>48.006</td>
<td>32.512</td>
<td>34.036</td>
<td>70.443</td>
<td>57.658</td>
</tr>
<tr>
<td>0.35</td>
<td>47.752</td>
<td>39.624</td>
<td>43.180</td>
<td>30.480</td>
<td>13.462</td>
<td>36.491</td>
<td>18.627</td>
<td>34.036</td>
<td>64.008</td>
<td>57.658</td>
</tr>
<tr>
<td>0.40</td>
<td>47.752</td>
<td>39.624</td>
<td>43.180</td>
<td>21.336</td>
<td>13.462</td>
<td>13.462</td>
<td>11.684</td>
<td>34.036</td>
<td>35.576</td>
<td>57.658</td>
</tr>
<tr>
<td>0.45</td>
<td>37.423</td>
<td>30.141</td>
<td>16.764</td>
<td>16.764</td>
<td>0.000</td>
<td>13.462</td>
<td>11.684</td>
<td>11.345</td>
<td>22.680</td>
<td>11.430</td>
</tr>
<tr>
<td>0.50</td>
<td>16.764</td>
<td>25.400</td>
<td>16.764</td>
<td>16.764</td>
<td>0.000</td>
<td>8.975</td>
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</table>
number of available measured runoff should be omitted.

Table 7.12 shows that 126 runoff ordinates are available for cell number 14 of Watershed 11.

Measured runoff data

For each cell for which the value for available measured runoff is greater than zero a set of values of measured runoff discharge $Q_0(j,i)$ is given. Values given are the discharge for cell $j$ at the end of each time interval $(i)$ in units of $m^3/s$ (Table 7.13). The information in this section should also be omitted if all the values of the runoff indicator are less than 3.

7.4 CELLMOD – model computation

During and after reading the input data, the program involved a few computing operations.

Table 7.14 provides a listing of the model cells, the area of each cell being expressed as a ratio of that area to the total area of the watershed. The total area upstream of the outlet of each cell is also expressed as a ratio to the total area of the watershed and the length of the stream in each cell is expressed as a ratio of the main stream for the entire watershed.

Table 7.15 presents the computation of the saturation hydraulic conductivity, $K_s$, as a function of the bare soil hydraulic conductivity, $K_{s\text{bar}}$, percent of canopy cover, $CC$, and percent of ground cover $GC$ (Eq. 4.9). The calculation of this parameter is for each polygon represented by a rain gage.

Table 7.16 presents the rainfall excess as a result of the Green and Ampt calculations (Chapter 4) for each time interval and for each polygon. The
CHAPTER 7. MODEL OPERATION

Table 7.12: Number of available observed ordinates for the storm of Aug. 12, 1971 (6).

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IC - Identifying number of cell.
NQC - Number of available observed runoff ordinates.

Table 7.13: Observed runoff data for cell number 14, for the storm of Aug. 12, 1971 (6).

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## Table 7.14: Model cells structure calculations

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**IC** - identifying number of cell.
**ALF** - size of cell, ratio to the area of the watershed.
**CUM A** - cumulative area, ratio to the area of the watershed.
**LENGTH** - length of stream, ratio to the main stream length.

Mean cell area 0.449 sq.km.
Mean cell length 0.916 km.
### Table 7.15: Calculation of the saturated hydraulic conductivity.

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<th>GC</th>
<th>Ks</th>
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- **ng** = Field number of rain gage.
- **Ksbar** = Saturated conductivity for bare soil in mm/hr.
- **CC** = Canopy cover in percent.
- **GC** = Ground cover in percent.
- **Ks** = Saturated hydraulic conductivity in mm/hr.
Table 7.16: Rainfall excess calculated by the Green and Ampt equation for unsteady rainfall, for the storm of Aug. 12, 1971.

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\[ n_g = \text{Field number of rain gage.} \]

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rainfall excess data is assigned to the model cells by the Thiessen weight procedures as explained in Chapter 6 (Table 6.5).

Rainfall and runoff data for the entire watershed presented in Table 7.17 are listed at time intervals and include the following information: time \((T)\) in hours, mean rate of rainfall \((P)\) over the watershed in \(mm/hr\), mean rate of rainfall excess \((RE)\) over the watershed in \(mm/hr\), specific measured discharge \((QS)\) per unit area of the watershed as measured at the outlet in \(mm/hr\), and cumulative total rainfall \((SR)\) over the watershed in \(mm\) and cumulative measured runoff \((SQ)\) at the outlet of the watershed.

Values of the first moments of the rainfall excess hyetograph, of the runoff hydrograph and of the unit hydrograph are presented in Table 7.18. All moments are expressed in units of hours.

Table 7.19 gives the following information for each of the cell model: the cell identifying number, \(IC\), the value of the surface storage coefficient, \(K\), the channel storage coefficient, \(Kc\), and the channel time shift, \(tc\). All terms are expressed in hours and calculated by Eqs. 3.20, 3.23 and 3.24, respectively.

The next table (Table 7.20) presents the calculation of channel losses in \(m^3/s\) for each interior cell as a function of the length of the channel \((CLE)\) in each cell and the average width \((CW)\).

The information produced at this stage (Table 7.21) is related to the production of rainfall excess and its conversion to surface outflow. The information given for each cell is the following: cell identifying number \((IC)\), the total rainfall input for each cell \((RTC)\) in \(mm\), the total depth of runoff due to rainfall excess for cell \((YTC)\) expressed in \(mm\), the total mean rainfall excess over the area contributing to the cell outlet \((REA)\) in
Table 7.17: Rainfall and runoff data for the entire watershed, for the storm of Aug. 12, 1971 (6).

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</tr>
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<td>3.4362</td>
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<td>0.0000</td>
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<td>5.0125</td>
<td>3.4362</td>
</tr>
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</table>
Table 7.18: Moments of storm data for the storm of Aug. 12, 1971 (6).

<p>| | |</p>
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<tr>
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<th></th>
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<tbody>
<tr>
<td>First moment of rainfall hyetograph</td>
<td>0.2083 hr.</td>
</tr>
<tr>
<td>First moment of runoff hydrograph</td>
<td>0.8245 hr.</td>
</tr>
<tr>
<td>First moment of unit hydrograph</td>
<td>0.6162 hr.</td>
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</tbody>
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Table 7.19: Cell parameters and routing information.

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<th>tc</th>
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<tbody>
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<td>0.050</td>
</tr>
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<td>0.256</td>
<td>0.107</td>
<td>0.032</td>
</tr>
<tr>
<td>3</td>
<td>0.323</td>
<td>0.112</td>
<td>0.034</td>
</tr>
<tr>
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<td>0.251</td>
<td>0.109</td>
<td>0.033</td>
</tr>
<tr>
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<td>0.319</td>
<td>0.133</td>
<td>0.040</td>
</tr>
<tr>
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<td>0.093</td>
<td>0.028</td>
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<td>0.069</td>
<td>0.021</td>
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<tr>
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<td>0.098</td>
<td>0.030</td>
</tr>
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<td>0.027</td>
</tr>
<tr>
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<td>0.059</td>
<td>0.018</td>
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<td>0.034</td>
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<td>0.107</td>
<td>0.032</td>
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<tr>
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<td>0.029</td>
<td>0.009</td>
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Table 7.20: Cell parameters and channel losses information.

<table>
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<th>IC</th>
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<th>CW</th>
<th>CA</th>
<th>CL</th>
<th>QCA</th>
</tr>
</thead>
<tbody>
<tr>
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<td>1.024</td>
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<td>5120.0</td>
<td>26.0</td>
<td>0.037</td>
</tr>
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<td>5124.0</td>
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<td>0.037</td>
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<tr>
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<td>0.634</td>
<td>12.0</td>
<td>7608.0</td>
<td>26.0</td>
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</tr>
<tr>
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<td>2487.0</td>
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<td>0.018</td>
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<td>5120.0</td>
<td>26.0</td>
<td>0.037</td>
</tr>
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<td>5.0</td>
<td>5245.0</td>
<td>26.0</td>
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<td>6.0</td>
<td>5856.0</td>
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<tr>
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<td>12.0</td>
<td>3216.0</td>
<td>26.0</td>
<td>0.023</td>
</tr>
</tbody>
</table>

IC = Identifying number of cell.
CLE = Channel length, in km.
CW = Channel width, in m.
CA = Channel area, in sq. m.
CL = Constant channel loss in mm/hr.
QCA = Channel losses in cu.m./s.
CHAPTER 7. MODEL OPERATION

Table 7.21: Cell rainfall, runoff and peak discharge for the storm of Aug. 12, 1971 (6).

<table>
<thead>
<tr>
<th>IC</th>
<th>RTC</th>
<th>UTC</th>
<th>REA</th>
<th>YTA</th>
<th>YCM</th>
<th>YTM</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>19.474</td>
<td>5.056</td>
<td>5.056</td>
<td>5.056</td>
<td>1.680</td>
<td>1.680</td>
</tr>
<tr>
<td>2</td>
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<td>7.324</td>
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<td>7.324</td>
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<td>1.826</td>
</tr>
<tr>
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<td>23.711</td>
<td>9.847</td>
<td>7.623</td>
<td>6.822</td>
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</tr>
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<td>4</td>
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<td>6.193</td>
<td>1.598</td>
<td>5.482</td>
</tr>
<tr>
<td>5</td>
<td>18.552</td>
<td>5.943</td>
<td>5.943</td>
<td>5.943</td>
<td>1.959</td>
<td>1.959</td>
</tr>
<tr>
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<td>6.308</td>
<td>5.255</td>
<td>1.445</td>
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<tr>
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<td>7.813</td>
<td>7.260</td>
<td>5.549</td>
<td>1.140</td>
<td>8.025</td>
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<tr>
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<td>3.456</td>
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<td>0.760</td>
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<td>2.511</td>
<td>1.709</td>
<td>0.559</td>
<td>1.324</td>
</tr>
<tr>
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<td>2.562</td>
<td>2.528</td>
<td>1.593</td>
<td>0.867</td>
<td>1.263</td>
</tr>
<tr>
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<td>2.096</td>
</tr>
<tr>
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<td>3.738</td>
<td>2.571</td>
<td>2.199</td>
<td>3.238</td>
</tr>
<tr>
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<td>17.485</td>
<td>6.441</td>
<td>5.535</td>
<td>3.833</td>
<td>0.557</td>
<td>10.754</td>
</tr>
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</table>
mm, the total runoff depth at the outlet of each cell ($Y TA$) in $mm$, the maximum discharge due to rainfall excess for each cell ($Y CM$) in $m^3/s$ and the maximum of the total cell outflow runoff hydrograph for each cell ($Y TM$) in $m^3/s$.

7.5 Results

7.5.1 Results of individual cells

The information produced at this stage depends on the values specified previously, for the output indicator $I PT$ for each cell. If the value assigned to the indicator $I PT$ is zero no output will be produced for that cell. If the value of the indicator is $I PT = 1$ for any cell, then for that cell Table 7.22 will produced the following values: time ($T$) in hours, the total predicted outflow discharge ($Y A$) in $m^3/s$, cumulative depth of predicted runoff ($A Y$) in $mm$.

If the value of the indicator is $I PT = 2$ a plot of the computed discharge in $m^3/s$ (Fig. 7.3) as a function of time in hours is produced in addition to the Table 7.22.

If the value of the indicator is $I PT = 3$ then the above table is expanded to include values of observed discharge ($Q O$) at the outlet of the cell concerned in $m^3/s$ and the cumulative observed runoff ($A Q$) in $mm$. A listing of the differences ($Y A - Q O$) in $m^3/s$ is also included. The plot produced in the case of $I PT = 3$ (Fig. 7.3) gives the observed discharge as well as the predicted discharge for each increment of time. If the two values are equal or very close to each other only the predicted value is plotted.
Table 7.22: Results for cell no. 14, for the storm of Aug. 12, 1971 (6).

<table>
<thead>
<tr>
<th>T</th>
<th>YA</th>
<th>AY</th>
<th>QB</th>
<th>AQ</th>
<th>DQY</th>
</tr>
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<tbody>
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<td>0.0000</td>
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<td>0.0000</td>
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<td>0.0000</td>
<td>0.0000</td>
</tr>
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<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
</tr>
<tr>
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<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
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<td>0.0769</td>
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<td>0.0283</td>
<td>0.1180</td>
<td>0.0041</td>
<td>1.2578</td>
</tr>
<tr>
<td>0.3500</td>
<td>3.4608</td>
<td>0.0976</td>
<td>1.5970</td>
<td>0.0287</td>
<td>1.8638</td>
</tr>
<tr>
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<td>0.2328</td>
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<td>0.1241</td>
<td>0.9091</td>
</tr>
<tr>
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<td>8.1500</td>
<td>0.4351</td>
<td>7.7100</td>
<td>0.3071</td>
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<td>0.8023</td>
<td>1.0466</td>
</tr>
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<td>9.7850</td>
<td>1.0767</td>
<td>0.9693</td>
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<td>0.5070</td>
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<td>-0.4730</td>
</tr>
</tbody>
</table>

T = Time, in hr.
YA = Predicted discharge, in cu.m./s.
AY = Cumulative predicted runoff, in mm.
QB = Observed discharge, in cu.m./s.
AQ = Cumulative observed runoff, in mm.
DQY = Difference between predicted and observed discharge, in cu.m./s.
Table 7.22 (cont.):

<table>
<thead>
<tr>
<th>T</th>
<th>YA</th>
<th>AY</th>
<th>QB</th>
<th>AQ</th>
<th>DQY</th>
</tr>
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<td>0.3900</td>
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<td>-0.3889</td>
</tr>
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</tr>
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<td>3.3861</td>
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<td>-0.1380</td>
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<td>2.6500</td>
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<td>2.7500</td>
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<td>3.8330</td>
<td>0.1140</td>
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</tr>
<tr>
<td>2.8000</td>
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<td>3.0000</td>
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<td>-0.0730</td>
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<tr>
<td>3.2500</td>
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<td>0.0400</td>
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<td>-0.0400</td>
</tr>
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<tr>
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<td>3.8330</td>
<td>0.0260</td>
<td>3.4320</td>
<td>-0.0260</td>
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<td>3.4000</td>
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<td>3.8330</td>
<td>0.0230</td>
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<td>3.4353</td>
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<td>3.8330</td>
<td>0.0120</td>
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<td>3.8330</td>
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<td>-0.0100</td>
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<td>3.8000</td>
<td>0.0000</td>
<td>3.8330</td>
<td>0.0000</td>
<td>3.4362</td>
<td>0.0000</td>
</tr>
</tbody>
</table>
Figure 7.3: Observed and predicted hydrographs for the storm of Aug. 12, 1971 (6).
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Table 7.23: Summary of results for the storm of Aug. 12, 1971 (6).

<table>
<thead>
<tr>
<th></th>
<th>Predicted</th>
<th>Observed</th>
<th>Predicted to observed ratio (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average rainfall (mm)</td>
<td>17.7225</td>
<td>17.7225</td>
<td></td>
</tr>
<tr>
<td>Total runoff (mm)</td>
<td>3.8330</td>
<td>3.4362</td>
<td>-10.353</td>
</tr>
<tr>
<td>Total volume (cu.m)</td>
<td>24071.28</td>
<td>21579.13</td>
<td>-10.353</td>
</tr>
<tr>
<td>Peak discharge (cu.m./s.)</td>
<td>10.7543</td>
<td>9.7850</td>
<td>-9.013</td>
</tr>
<tr>
<td>Time to peak (hr.)</td>
<td>0.60</td>
<td>0.60</td>
<td></td>
</tr>
</tbody>
</table>

Table 7.24: Computing deviation statistic for the storm of Aug. 12, 1971 (6).

- Absolute deviation between time to peak = 0.000 hr.
- Mean absolute deviation = 0.3981 cu.m./s.
- Mean root square deviation = 0.6065 cu.m./s.
- Mean of weighted absolute deviation = 0.4636 cu.m./s.
- Maximum absolute deviation = 1.8638 cu.m./s.
- Absolute deviation between peaks = 0.9693 cu.m./s.
- Number of positive points deviations = 24
- Number of negative points deviations = 48
- Number of zero points deviations = 4
Chapter 8

MODEL EVALUATION AND RESULTS

8.1 Introduction

The aim of the evaluation procedure is to fit the predicted results, as closely as possible, to the observed data and then to analyze the degree of errors or goodness of fit. In this study the evaluation procedure includes these steps: (1) trial and error calibration; (2) sensitivity analysis; (3) bilinear interpolation optimization; (4) testing the model on different storm events; and (5) testing the model on a different watershed. This chapter also presents the results for each storm event including the predicted and observed hydrographs, summary of results and the computed deviation statistics.

8.2 Objective functions

The evaluation procedure is made with reference to a specified objective function. An objective function is defined as a mathematical expression of difference between the predicted and the observed data during the calibration period (Diskin and Simon, 1977). The objective function is designed
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to reduce this difference to a minimum, or, as an alternative, to calculate the maximization of a likelihood function. To avoid bias, the above authors recommended judging the model performance with reference to a number of objective functions rather than to a single function.

Of a large number of objective functions that have been defined in the literature (e.g. Diskin and Simon, 1977), only a selected list is presented below:

1. Predicted to observed total runoff ratio:

\[ PVAT = \left( \frac{VQT \cdot 100}{VAT} \right) - 100 \]  \hspace{1cm} (8.1)

where \( PVAT \) is the percent of the predicted runoff volume, \( VAT \), from the observed runoff volume, \( VQT \), expressed in \( mm \) or \( m^3 \). \( PVAT \) can be either positive when the observed value is greater than the predicted, zero in case of no deviation, or negative – otherwise. In other words, Eq. 8.1 answers the question “what percentage should one increase or decrease the predicted runoff in order to match the observed value?”.

2. Predicted to observed peak discharge ratio:

\[ PYMX = \left( \frac{QMX \cdot 100}{YMX} \right) - 100 \]  \hspace{1cm} (8.2)

where \( PYMX \) is the percent of the predicted peak discharge and \( YMX \) from the observed peak discharge, \( QMX \), expressed in \( m^3/s \).

3. Mean absolute discharge deviation, \( SMA \):

\[ SMA = \frac{1}{n} \sum_{i=1}^{n} |YA(i) - QB(i)| \]  \hspace{1cm} (8.3)

where \( YA \) and \( QB \) are, respectively, the predicted and observed discharge in a specific time increment \( i \).
CHAPTER 8. MODEL EVALUATION AND RESULTS

4. Mean root square discharge deviation, $SME$:

$$SME = \sqrt{\frac{1}{n} \sum_{i=1}^{n} |YA(i) - QB(i)|^2} \quad (8.4)$$

5. Mean of weighted absolute discharge deviation, $SWD$:

$$SWD = \frac{1}{n} \sum_{i=1}^{n} W |YA(i) - QB(i)| \quad (8.5)$$

where $W$ signifies a double weight assigned to the deviation values which are greater than half of the observed peak discharge. This procedure tends to give extra weight to the large runoff values.

6. Maximum absolute discharge deviation, $DMX$:

$$DMX = \max_i |YA(i) - QB(i)| \quad (8.6)$$

7. Absolute deviation between peaks, $PDF$:

$$PDF = |YM - QM| \quad (8.7)$$

where $YM$ and $QM$ are the predicted and observed peak discharge, respectively, in $m^3/s$.

8.3 Trial and error calibration

The trial and error calibration procedure is a visual method of adjusting the predicted hydrograph to match or replicate the observed hydrograph. As discussed in the previous chapters, after reducing the number of the parameters, the model remained with 8 operative parameters for the evaluation procedure (Table 8.1). There are two different types of parameters.
### Table 8.1: Model parameters.

<table>
<thead>
<tr>
<th>A. Routing parameters:</th>
<th>Notation</th>
<th>Dimensions</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Reservoir coefficient</td>
<td>AKC</td>
<td>hr</td>
</tr>
<tr>
<td>2. Routing coefficient</td>
<td>TKF</td>
<td>hr</td>
</tr>
<tr>
<td>3. Time delay factor</td>
<td>TDF</td>
<td>hr</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>B. Infiltration parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>4. Matric potential</td>
</tr>
<tr>
<td>5. Saturated conductivity</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>C. Channel losses parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>6. Constant Channel loss</td>
</tr>
<tr>
<td>7. Initial loss ratio</td>
</tr>
<tr>
<td>8. Loss decay factor</td>
</tr>
</tbody>
</table>
The first type includes the physical based parameters — the saturated hydraulic conductivity, $K_s$, and the constant channel loss parameter, $QCA$. The values of these parameters are either directly measured or characterized by physical-based functions. It should be noted that to simplify the evaluation procedure, weighted average values of the parameters $K_s$ and $QCA$ were used and their spatial variability has not yet been taken into account.

The second type of parameter has no physical meaning and can be termed as a fitting parameter. In this stage of the evaluation the effective matric potential, $SM$, is treated as a fitted parameter. The trial and error calibration was limited only to the fitted parameters.

### 8.4 Sensitivity analysis

"Sensitivity analysis is a technique for assessing the relative change in a model response or output resulting from a change in inputs or in model parameters" (Lane and Ferreira 1980, p. 113). One of the techniques for sensitivity analysis, applied especially for simple explicit models, is to take derivatives of the output with respect to input or parameters and express the results as an explicit function. For more complex models other techniques are usually used such as differentials, relative change, graphs or tables.

The relative change approach is used in the current study. Using this technique, the values of the parameters (which were obtained by the trial and error calibration) are changed by incrementing each of the parameters in turn by a small amount of equal relative magnitude, $+5\%$, $+10\%$, $-5\%$ and $-10\%$, while the other parameters are held constant at their original
values. The resulting values of the change in the value of the objective function will be a measure of the model sensitivity to changes in the parameter's values. By comparing the sensitivity of the model with respect to the various parameters one can indicate how the parameters influence the values of the objective functions (Diskin, 1970).

Table 8.2 shows an example of the sensitivity analysis of the effective matric potential parameter, $SM$, for the storm of Aug. 12, 1971 (6) and for the objective functions which describe the goodness of fit of the predicted volume and of the predicted peak discharge. The linear relationships obtained from this table are plotted in Fig. 8.1 and will be used later for the model optimization.

### 8.5 Bilinear optimization

Before continuing to the next step, model calibration with optimized parameters, one of the above objective functions should be selected to be used in the optimization scheme. As mentioned earlier, it is recommended to use more than one objective function in order to avoid bias.

In the present study, the optimization procedure is based on two objective functions: (1) predicted to observed total runoff ratio (Eq. 8.1); and (2) predicted to observed peak discharge ratio (Eq. 8.2). These objective functions were selected because the flow volume and the peak discharge are widely used for many engineering applications. As will be presented below, these two objective functions will be used simultaneously in the optimization procedure while the others will be used as measures of the model performance.

Once the objective functions have been selected, it is necessary to min-
CHAPTER 8. MODEL EVALUATION AND RESULTS

Figure 8.1: Sensitivity analysis for the storm of Aug. 12, 1971 (6).
imize simultaneously the differences between the predicted and observed runoff volume and between the predicted and observed peak discharge in order to fulfill the criterion of efficiency for the optimization scheme. Combining these two objective functions yield a new function

\[ FUNC = |PVAT + PYMX| \] (8.8)

Therefore, the optimal values of the model parameters are those which give the minimum value of the above defined criterion of efficiency (Eq. 8.8).

This efficiency criterion can be performed by using a bilinear interpolation technique. The procedure described below takes advantage of the linear relationships between the effective matric potential parameter \((SM)\) and the objective functions defined by the ratio between the predicted and observed volume \((PVAT)\) and the ratio between predicted and observed peak discharge \((PYMX)\).

The following steps are proposed for the optimization procedure, demonstrated with the example of the storm of Aug. 12, 1971 (6):

1. From the trial and error procedure it was found that \(SM = 11.00\ mm\) is close for fitting the predicted hydrograph to the observed but it is not the optimal value. Results of the trial and error calibration are presented in the first column of Table 8.3 and in Fig. 8.2. It can be seen that both the observed runoff volume and the observed peak discharge are larger than the respective predicted values. In order to obtain a perfectly matched runoff volume one should increase the predicted value by 8.46 percent and similarly, in order to obtain a perfectly matched peak discharge one should increase the predicted value by 5.98 percent. The combined objective function defined in
Table 8.2: Program CELLMOD, sensitivity analyses of the effective matric potential parameter for the storm of Aug. 12, 1971 (6).

<table>
<thead>
<tr>
<th>Change (%)</th>
<th>SM (mm)</th>
<th>VAT (m^3)</th>
<th>PVAT (%)</th>
<th>QMX (m^3/s)</th>
<th>PQMX (%)</th>
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</thead>
<tbody>
<tr>
<td>+10</td>
<td>12.11</td>
<td>18431.</td>
<td>-7.280</td>
<td>8.642</td>
<td>-6.327</td>
</tr>
<tr>
<td>+5</td>
<td>11.56</td>
<td>19096.</td>
<td>-3.937</td>
<td>8.923</td>
<td>-3.285</td>
</tr>
<tr>
<td>0</td>
<td>11.00</td>
<td>19878.</td>
<td>0.000</td>
<td>9.226</td>
<td>0.000</td>
</tr>
<tr>
<td>-5</td>
<td>10.46</td>
<td>20666.</td>
<td>3.960</td>
<td>9.535</td>
<td>3.345</td>
</tr>
<tr>
<td>-10</td>
<td>9.91</td>
<td>21666.</td>
<td>8.994</td>
<td>9.914</td>
<td>7.454</td>
</tr>
</tbody>
</table>

Table 8.3: Calibration/optimization procedure. Comparison of results for the storm of Aug. 12, 1971 (6).

<table>
<thead>
<tr>
<th>Trial and Error Calibration</th>
<th>Prediction by Optimization</th>
<th>Prediction by API model</th>
</tr>
</thead>
<tbody>
<tr>
<td>21579.13</td>
<td>21579.13</td>
<td>21579.13</td>
</tr>
<tr>
<td>9.7850</td>
<td>9.7850</td>
<td>9.7850</td>
</tr>
<tr>
<td>11.000</td>
<td>9.989</td>
<td>8.376</td>
</tr>
<tr>
<td>19895.43</td>
<td>21543.49</td>
<td>24071.28</td>
</tr>
<tr>
<td>9.2327</td>
<td>9.8669</td>
<td>10.7543</td>
</tr>
</tbody>
</table>

Evaluation:

<table>
<thead>
<tr>
<th>Result Description</th>
<th>Trial and Error Calibration</th>
<th>Prediction by Optimization</th>
<th>Prediction by API model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Predicted to Observed Runoff Ratio, PVAT (%)</td>
<td>8.463</td>
<td>0.165</td>
<td>-10.353</td>
</tr>
<tr>
<td>Predicted to Observed Peak Discharge, PYMX (%)</td>
<td>5.982</td>
<td>-0.830</td>
<td>-9.013</td>
</tr>
<tr>
<td>Combined Objective Function, FUNC (%)</td>
<td>14.445</td>
<td>0.665</td>
<td>19.366</td>
</tr>
</tbody>
</table>
Figure 8.2: Hydrographs for different stages of evaluation, for the storm of Aug. 12, 1971 (6).
Eq. 8.8 yields

\[ \text{FUNC} = |8.463 + 5.982| = 14.445\% \quad (8.9) \]

2. From the sensitivity analysis results (Table 8.2) it can be seen that there are linear relationships between the percentage of change of \( PVAT \) and \( PYMX \) and the percentage of change of \( SM \). These relationships are illustrated in Fig. 8.1 for the storm of Aug. 12, 1971 (6).

3. In order to obtain optimal results both for the runoff volume and the peak discharge, the bilinear interpolation algorithm was developed (Table 8.4). This algorithm calculates separately the regression lines for the runoff volume points and for the peak discharge points which are obtained from the sensitivity analysis table. Next it calculates separately the new \( SM \) values for each of these cases, given the percentages of change from Table 8.3 (\( PVAT = 8.463 \) and \( PYMX = 5.982 \)). Finally, the algorithm calculates the mean \( SM \) value from the new \( SM \) values.

4. Running the model again with the optimized value \( SM = 9.999 \) produces the best fitted predicted hydrograph as presented in the second column of Table 8.3 and in Fig. 8.2. From this table it can be seen that the combined objective function gives

\[ \text{FUNC} = |0.165 + (-0.803)| = 0.638\% \quad (8.10) \]

which is a relatively small value. Any further change in the \( SM \) will
Table 8.4: Bilinear algorithm for model optimization. Example for the storm of Aug. 12, 1971 (6).

Step 1 - Runoff Volume:

<table>
<thead>
<tr>
<th>CHANGE (%)</th>
<th>PVAT (%)</th>
<th>SM (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>+10</td>
<td>-7.280</td>
<td>12.113</td>
</tr>
<tr>
<td>+5</td>
<td>-3.937</td>
<td>11.563</td>
</tr>
<tr>
<td>0</td>
<td>0.000</td>
<td>11.000</td>
</tr>
<tr>
<td>-5</td>
<td>3.960</td>
<td>10.461</td>
</tr>
<tr>
<td>-10</td>
<td>8.994</td>
<td>9.911</td>
</tr>
</tbody>
</table>

Given new PVAT value = 8.555
Predicted new SM value = 9.898

Step 2 - Peak Discharge:

<table>
<thead>
<tr>
<th>CHANGE (%)</th>
<th>PVAT (%)</th>
<th>SM (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>+10</td>
<td>-6.327</td>
<td>12.113</td>
</tr>
<tr>
<td>+5</td>
<td>-3.285</td>
<td>11.563</td>
</tr>
<tr>
<td>0</td>
<td>0.000</td>
<td>11.000</td>
</tr>
<tr>
<td>-5</td>
<td>3.345</td>
<td>10.461</td>
</tr>
<tr>
<td>-10</td>
<td>7.454</td>
<td>9.911</td>
</tr>
</tbody>
</table>

Given new PYMX value = 6.059
Predicted new SM value = 10.075

Step 3 - Mean Predicted New SM Value = 9.987
introduce a larger combined error for the runoff volume and the peak discharge.

8.6 Forecasting procedure

It should be noted that the calibration/optimization procedure described above helps in refining the predicted hydrograph to match the observed one. However, in the forecasting version of CELLMOD, an objective procedure for evaluating the soil moisture condition prior to the storm event is needed. As discussed in Chapter 5, the effective matric potential, $SM$, is a function of four parameters (Eq. 5.17). Two of them, $S_f$ and $n_*$, are related to the soil texture and therefore do not change with time. The parameters $T$ and $DF$ are obtained from the API model. The former is a constant parameter and the latter is a variable which should be introduced from the API model results for each storm event. Consequently, the performance of the API model has a great influence on the differences between the observed and predicted hydrographs.

It was calculated (Eq. 5.18) that the effective matric potential for the storm event of the Aug. 12, 1971 (6) is $SM = 8.376$. Running CELLMOD with this parameter value produces the results presented in the third column of Table 8.3 and in Fig. 8.2. It can be seen that according to the objective functions these are the worst results among the three cases.

8.7 Results

Twenty one storm event data sets (rainfall and runoff) are available for Watershed 11 between the years 1966 and 1982. These included all the larger events with reliable data. In addition seven of these storm events
contain data for Watershed 8 (as mentioned in Section 7.2 Watershed 11 is a part of Watershed 8).

Eleven of the storm events of Watershed 11 (event number 1 through 11) were selected for the model calibration. In addition, two types of model testing were used: (1) testing the model on other storm events on the same watershed (events numbered 12 through 21); and (2) testing the model on another watershed with 7 data sets of Watershed 8 (events numbered 4, 13–15, 18–20).

There are three types of results: (1) results of the calibration events; (2) results of the tested events; and (3) results of the forecasting procedure. Tables 8.5 and 8.6 presents the summary of results and statistics for the calibration and test events for Watershed 8 and 11. It can be seen that according to the main objective function \((FUNC, \text{Eq. 8.8})\) the mean is \(2.2295\% \pm 3.238\%\) for all the events. Very high correlations (the portion of variability explained, \(r^2\), above 0.96) are obtained between the observed and predicted volume and between the observed and predicted peak discharge (Figs. 8.3 – 8.8) both for the calibration and the test events.

Relatively larger errors were obtained for the forecasting mode than for calibrated and tested modes as shown in Tables 8.7 and 8.8 for all the objective functions. From the correlation plots (Figs. 8.9 and 8.10) it can be seen that the model produced relatively lower correlations (\(r^2 = 0.806\) and \(r^2 = 0.771\) for volume and peak discharge, respectively) for Watershed 11. For the forecasting mode of Watershed 8, relatively high correlations were obtained (\(r^2 = 0.976\) and \(r^2 = 0.956\) for volume and peak discharge, respectively, Figs. 8.11 and 8.12), however, significant bias was obtained in the volume forecasting case.

Appendix B presents the hydrographs for all the 28 events. Each plot
### Table 8.5: Summary of results of the calibrated and tested events of Watersheds 11 and 8.

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<th>Event No.</th>
<th>Date (m/d/y)</th>
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<th>VAT (m³)</th>
<th>PVAT (%)</th>
<th>YMX (m³/s)</th>
<th>QMX (m³/s)</th>
<th>PYMX (%)</th>
<th>FUNC (%)</th>
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**Absolute Mean**

- P: 16.282
- VQT: 15.625
- VAT: 3.228

**Standard Deviation**

- P: 10.478
- VQT: 11.000
- VAT: 5.520

---

### Watershed 11, Test

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**Absolute Mean**

- P: 12.914
- VQT: 12.214
- VAT: 1.741

**Standard Deviation**

- P: 7.207
- VQT: 7.929
- VAT: 1.694
Table 8.5 (Cont.)

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### Table 8.6: Summary of deviation statistics of the calibrated and tested events of Watersheds 11 and 8.

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Figure 8.3: Observed vs. predicted runoff volume for Watershed 11, calibration events.
Figure 8.4: Observed vs. predicted peak discharge for Watershed 11, calibration events.
Figure 8.5: Observed vs. predicted runoff volume for Watershed 11, test events.
CHAPTER 8. MODEL EVALUATION AND RESULTS

Figure 8.6: Observed vs. predicted peak discharge for Watershed 11, test events.
Figure 8.7: Observed vs. predicted runoff volume for Watershed 8, test events.
Figure 8.8: Observed vs. predicted peak discharge for Watershed 8, test events.
Table 8.7: Summary of results of the forecasting procedure of Watersheds 11 and 8.

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Absolute Mean  30.082  14.674  58.660
Standard Deviation  18.510  9.324  41.360
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| Absolute Mean | 46.683 | 22.995 | 71.426 |
| Standard Deviation | 14.837 | 16.040 | 55.353 |

All Events

| Absolute Mean | 34.232 | 31.942 | 61.855 |
| Standard Deviation | 18.876 | 24.256 | 44.492 |
### Table 8.8: Summary of deviation statistics of the forecasting procedure of Watersheds 11 and 8.

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**Mean**

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**Standard Deviation**

0.97 1.77 1.14 6.16 2.88
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All Events
| Mean          | 1.82 | 3.04 | 2.23 | 11.53 | 4.21 |
| Standard Deviation | 1.24 | 2.02 | 1.56 | 8.97  | 2.74 |
Figure 8.9: Observed vs. predicted runoff volume for Watershed 11, forecasting events.
Figure 8.10: Observed vs. predicted peak discharge for Watershed 11, forecasting events.
Figure 8.11: Observed vs. predicted runoff volume for Watershed 8, forecasting events.
Figure 8.12: Observed vs. predicted peak discharge for Watershed 8, forecasting events.
contains three hydrographs — the observed one, the predicted by optimization hydrograph and the hydrograph which is calculated by the forecasting procedure.

8.8 Discussion and conclusions

By selecting two objective functions rather than a single one the user is able to utilize the model for more applications, however greater error is introduced into the results. The bilinear interpolation technique proposed by this study has the advantage of minimizing simultaneously the differences between the observed and predicted volume and peak discharge.

In the calibration stage the effective matric potential parameter was selected to adjust the observed and predicted hydrograph. This parameter has two properties — first it changes linearly the two objective functions, and also it has a precise physical meaning. With these two properties it was possible to calibrate the model and to use this parameter as a variable for the forecasting mode.

Acceptable results were obtained for the predicted mode of the two watersheds and for the forecasting mode of Watershed 11 (Figs. 8.5 - 8.10). For understanding the pronounce bias of the Watershed 8 forecasted volume (Fig. 8.11) additional analyses are required. The trial and error calibration procedure was repeated for Watershed 8 disregarding the calibration that had been done previously for Watershed 11. It was found that satisfactory calibration can be achieved by changing only the channel parameters $K_c$ and $PLS$ which affect the channel storage and the transmission losses, respectively (Figs. 8.13 and 8.14). In the new calibration the channel storage parameter is relatively smaller and the channel loss parameter is relatively
WATERSHED 8
CALIBRATION EVENTS
$r^2=0.984$

Figure 8.13: Observed vs. predicted runoff volume for Watershed 8, calibration events.
Figure 8.14: Observed vs. predicted peak discharge for Watershed 8, calibration events.
larger. It can be concluded that more attention should be paid to the differences in the channel characteristics. Since the equations used in this study include the channel size characteristics, perhaps other parameters such as depth or volume of the alluvium or its initial soil moisture content are necessary. Using the new calibrated parameters better forecasting results are obtained (Figs. 8.15 – 8.16).
Figure 8.15: Observed vs. predicted runoff volume for Watershed 8, forecasting events (after calibration).
WATERSHED 8 FORECASTING

Figure 8.16: Observed vs. predicted peak discharge for Watershed 8, forecasting events (after calibration).
Chapter 9

SUMMARY AND CONCLUSIONS

The objective of this study was to develop, calibrate and test a method for forecasting storm runoff from semi-arid watersheds using an available prediction rainfall-runoff model.

The model called CELLMOD was found to be a suitable model for this study because of its structure. This model divides the watershed into subunits which have about the same size as the data received from available data sources such as soil surveys or remote sensing devices.

In order to turn the predictive model into a design forecasting model three elements had to be modified:

1. An objective procedure was developed for evaluating the soil moisture deficit in the upper soil layer at the beginning of each storm event. The soil moisture deficit is a variable which is considered to be a most important factor involved in the rainfall-runoff relationships and is usually hard to measure or estimate. An API-type model was derived and tested with data from four different watersheds in southeastern Arizona. The model which is based on daily rainfall, appears to be
a practical tool for estimating the initial moisture deficit prior to a specific storm event.

2. Distinction was made between the physically-based parameters and the other fitting parameters. For this purpose a solution for the Green and Ampt infiltration equation was used to compute values of rainfall excess under unsteady rainfall conditions. The three parameters of the equation have physical significance and are obtained from the soil properties: (1) The saturated hydraulic conductivity is obtained from the bare soil saturated hydraulic conductivity and is then modified using data on the canopy cover and ground cover. The canopy and ground cover can be partially determined by remote sensing; (2) The difference in average capillary potential is obtained from the effective porosity and the average potential. Both are functions of the soil texture; (3) The difference in average soil moisture is obtained from the API procedure. Although the index does not rely on soil characteristics, it was found that the soil moisture deficit reflects the soil texture of the watershed.

3. For the physically-based parameters a geographic information system (GIS) was utilized. The GIS was used to account for the variability in time and space of the input data and the watershed characteristics and to coregister variables and parameters on a common basis by using the grid-cell overlay operation. Therefore, the GIS plays an important role in operating a semi-distributed rainfall-runoff model.

The fitting parameters together with the physically-based parameters were used to calibrate the model on one subwatershed in the Walnut Gulch
Experimental Watershed (Watershed 11). Because the physically based parameters were deduced from the soil characteristics they remained constant during the calibration procedure. On the other hand, by changing the fitting parameters' values a trial and error calibration procedure was used to match as closely as possible the observed and calculated hydrographs.

Two objective functions were selected for the optimization procedure. These two expressed the goodness of fit between the calculated hydrograph volume and peak discharge and the observed hydrograph volume and peak discharge.

Taking advantage of the linear relationships between the effective matric potential parameter and the two objective functions obtained from the sensitivity analyses made it possible to develop a bilinear interpolation algorithm to minimize, simultaneously, the differences between the calculated and observed volume and peak discharge. It was found that this algorithm produces a minimum error with reference to the combined objective function and any further change in the parameter will introduce a larger combined error. Satisfactory results were achieved from testing the prediction mode of the model with data of other storm events of Watershed 11 and also of another watershed (Watershed 8). In the prediction mode the effective matric potential parameter was allowed to vary from storm to storm.

In the forecasting mode of the model the values of the effective matric potential parameter were estimated from the API model. Relatively larger errors were obtained in the forecasting mode than in the prediction mode. These errors were in part caused by the errors in estimation of the soil moisture deficit in the API model.

The overestimated runoff volume values in the forecasting mode of Watershed 8 can be explained by higher transmission losses as a result of larger
and deeper channels. These errors highlight some of the weaknesses of the model which was tested with one rainfall pattern (thunderstorms) on watersheds with ephemeral stream channels. It can be concluded that for applying the model to another watershed the model should be evaluated for the new conditions and the fitting parameters have to be a basis for a new calibration procedure.

Because of the structure of the model it is capable of using remotely sensed data. Although technical and administrative problems at the NWS at the Tucson International Airport caused difficulties in the weather radar data acquisition it was found that the radar can provide high resolution measurements of rainfall intensity that are continuous in time and space and give real-time dynamics of the storm cell. In the case of the weather radar located in Tucson, 100 km from the study area, a special computer program was developed in order to obtain the rainfall data in the polar coordinates of the radar (radar row data). The spatial resolution achievable by this program for an individual pixel is a function of the distance from the radar set and is computed to be 1x1.7 km over the study area. The radar antenna turns at three revolutions per minute therefore the time increments between individual radar scans can be as small as 0.33 min. However, in order to reduce the noise, it is recommended to use 3 minutes time increments which means integration of 9 radar antenna revolutions.

The weather radar might be used to supplement or replace the conventional rain gage stations and also as a data bank for the API-type model. A geographic information system connected with the radar processor can store the cumulative daily rainfall depth and calculate the soil moisture deficit prior to the storm event by the method suggested in this study.

In summary, the main contribution of the model is the methodology
which provides significant assistance in terms of design runoff forecasting. The proposed forecasting procedure can be used for various applications of planning, design and management of water resources and other engineering systems. The design forecasting concept is "one-step-ahead" prediction and it is believed by applying the model with weather radar data it can be used in real-time for flood forecasting and warning.
Appendix A

PROGRAM LISTING
APPENDIX A. PROGRAM LISTING

PROGRAM CELLMOD

******************************************************************
A SPATIALLY SEMI-DISTRIBUTED, PARAMETRIC MODEL FOR CONVERTING
RAINFALL EXCESS DIM
DIRECT SURFACE RUNOFF.

THE MODEL WRITTEN INITIALLY BY M.H. DISKIN (MARCH 1983),
MODIFIED BY A. KARNIELI MAY 1988 (VERSION CELLO10)

******************************************************************

PROGRAM CELLMOD(INPUT, OUTPUT, TAPE5=INPUT, TAPE6=OUTPUT)

CHARACTER TITLE(20), FNAME*64
REAL KS(40), KSB(40)
COMMON /DUM1/ IC(40), ID(41), IFI(40), ALF(40), KC(40,4), RIG(40)
COMMON /DUM2/ X(300), IC(40,300), NLC(40), SM(40)
COMMON /DUM3/ Y(300), Q(300), NRC(40), RC(40,300), QA(300), MM(40)
COMMON /DUM4/ SLC(40), U(40,200), R(40,300), CLE(40)
COMMON /DUM5/ QC(40,300), QB(300)
COMMON /DUM6/ NRG(40), NQC(40), NUC(40), ACT(40), RG(40,300)
COMMON /DUM7/ RIC(40), VC(40), VIM(40), YR(300), WT(40,40), TWT(40)
COMMON /DUM8/ YIC(40), RFT(40), REC(40), YTA(40), RE(40,300)
COMMON /DUM9/ PCC(40), PGC(40), QCA(40), CL(40), CW(40), CA(40)

WRITE (*, '(A)')' ENTER INPUT FILENAME'
READ (*, '(A)') FNAME
OPEN (5, FILENAME, STATUS='OLD')
WRITE (*, '(A)')' ENTER OUTPUT FILENAME'
READ (*, '(A)') FNAME
OPEN (6, FILENAME, STATUS='NEW')

----- READ WATERSHED INFORMATION
WRITE (6,100)
WRITE (6,140)
READ (5,104) TITLE
WRITE (6,105) TITLE
TITLE=IDENTIFICATION OF WATERSHED AND PROJECT
WRITE (6,102)
READ (5,113) AWS, STL, DT, TM
AWS=AREA OF WATERSHED IN SQ. KM.
STL=LENGTH OF THE MAIN STREAM IN KM.
DT= TIME INCREMENTS IN HRS.
IF (TM.GT.0) DT=DT/60
READ (5,115) NC, TWT, TLS
IWT = 0 FOR EQUAL SIZE FOR ALL CELLS.
IWT = 1 FOR AVAILABLE SIZE OF EACH CELL.
ISL = 0 FOR NO DATA OF STREAM LENGTH FOR EACH CELL.
APPENDIX A. PROGRAM LISTING

C ISL = 1 FOR AVAILABLE STREAM LENGTH FOR EACH CELL.
WRITE (6,123) AWS,STL,DT
IF (IWT.EQ.0) GO TO 5
READ (5,113) (ALF(J), J=1,NC)
C ALF(J)=SIZE OF CELL J, EXPRESSED IN SQ.KM., IN HA., OR AS A
C RATIO OF ITS AREA TO THE AREA OF THE WATERSHED.
SMA=0.0
DO 3 J=1,NC
SMA=SMA+ALF(J)
C SMA=CUMULATIVE AREA OF CELLS.
3 CONTINUE
DO 4 J=1,NC
ALF(J)=ALF(J)/SMA
4 CONTINUE
5 ANC=NC
IF (ISL.EQ.0) GO TO 7
READ (5,113) (CLE(J), J=1,NC)
READ (5,113) (CW(J),J=1,NC)
C CLE(J)= CHANNEL LENGTH IN CELL J IN KM.
C CW(J)= AVERAGE CHANNEL WIDTH IN CELL J IN M.
DO 6 J=1,NC
SLC(J)=CLE(J)/STL
6 CONTINUE
C ---- READING OF CELL DATA.
7 ANC=NC
SLM=0.0
DO 10 J=1,NC
READ (5,115) IC(J),ID(J),(KC(J,M),M-1,4)
C IC(J)=IDENTIFYING NUMBER OF CELL J.
C ID(J)=IDENTIFYING NUMBER OF CELL DOWNSTREAM OF CELL J.
C KC(J,M)=IDENTIFYING NUMBERS OF CELLS UPSTREAM OF CELL J.
C M=INDEX OF UPSTREAM CELLS.
IF (IWT.EQ.0) ALF(J)=1.0/ANC
IF (ISL.EQ.0) SLC(J)=1.7*SQRT(ALF(J)*AWS)/STL
C ---- COMPUTING CONTRIBUTION AREA FOR OUTLET OF EACH CELL.
ACT(J)=ALF(J)
C ACT(J)=CUMULATIVE RELATIVE AREA OF CELLS.
IT=0
DO 11 M=1,4
IT=IT+KC(J,M)
11 CONTINUE
IF (IT.EQ.0) GO TO 18
DO 16 M=1,4
MC=KC(J,M)
IF (MC.EQ.0) GO TO 16
ACT(J)=ACT(J)+ACT(MC)
16 CONTINUE
SLM = SLM + SLC(J)

CONTINUE

SLM = SLM / NC
SLA = SLM * STL

SLA = MEAN CELL LENGTH IN KM.

ARM = AWS / NC

ARM = MEAN CELL AREA IN SQ.KM.

WRITE (6, 102)
WRITE (6, 133) NC, ARM, SLA
WRITE (6, 116)

DO 9 J = 1, NC
WRITE (6, 111) IC(J), ID(J), (KC(J, M), M = 1, 4), ALF(J), ACT(J), SLC(J)

9 CONTINUE

WRITE (6, 102)

---- OUTPUT PRINTING INDICATOR
READ (5, 115) (IPT(J), J = 1, NC)

IPT(J) = INDICATOR FOR OUTPUT PRINTING.
IPT(J) = 0, NO PRINTING IS REQUIRED FOR OUTPUT OF CELL J.
IPT(J) = 1, PRINTING OF OUTPUT OF CELL J IS REQUIRED.
IPT(J) = 2, PRINTING & PLOTTING OF OUTPUT OF CELL J IS REQUIRED.
IPT(J) = 3, PRINTING & PLOTTING OF OUTPUT OF CELL J IS REQUIRED
WITH COMPARISON TO AVAILABLE DATA.

WRITE (6, 122)
WRITE (6, 115) (IC(J), J = 1, NC)
WRITE (6, 115) (IPT(J), J = 1, NC)
WRITE (6, 102)
READ (5, 115) NG, IRE, ICL

NG = NUMBER OF RAIN GAGES
IRE = RAINFALL EXCESS INDICATOR, IRE = 0 FOR AVAILABLE
RAINFALL VALUES ARE RAINFALL EXCESS
ICL = CHANNEL LOSS INDICATOR, ICL = 0 FOR NO CHANNEL LOSSES

---- READING THE FIELD NUMBER OF RAINGAGES
READ (5, 115) (MM(K), K = 1, NG)

MM = FIELD NUMBER OF RAINGAGES.

---- READING OF ROUTING PARAMETERS
READ (5, 113) AKC, TKF, TDF
WRITE (6, 124) AKC, TKF, TDF

PARAMETERS OF CELL MODEL:
AKC = RESERVOIR CONSTANT FOR CELL OF AVERAGE SIZE IN HRS.
TKF = ROUTING FACTOR FOR CELL OF AVERAGE SIZE IN HRS.
TDF = INITIAL TIME DELAY FOR CELL OF AVERAGE SIZE IN HRS.

---- READING THE INFILTRATION PARAMETERS
DO 80 K = 1, NG
SM(K) = 0.0
KSB(K) = 0.0
PCC(K) = 0.0
PGC(K) = 0.0
APPENDIX A. PROGRAM LISTING

80 CONTINUE
   IF (IRE.EQ.0) GO TO 32
   C READ THE EFFECTIVE MATRIC POTENTIAL PARAMETER
   READ (5,113) (SM(K), K=1,NG)
   C SM = EFFECTIVE MATRIC POTENTIAL, IN MM
   C READ THE SATURATED CONDUCTIVITY PARAMETERS
   READ (5,113) (KSB(K), K=1,NG)
   C KSB = SATURATED HYDRAULIC CONDUCTIVITY FOR BARE SOIL, IN MM/HR
   READ (5,113) (PCC(K), K=1,NG)
   C PCC = PRECENT OF CANOPY COVER IN EACH POLYGON
   READ (5,113) (PGC(K), K=1,NG)
   C PGC = PRECENT OF GROUND COVER IN EACH POLYGON.
   C CALCULATE THE HYDRAULIC CONDUCTIVITY FOR EACH POLYGON
   WRITE (6,125)
   WRITE (6,147)
   DO 81 K=1,NG
   KS(K)=KSB(K)*EXP(PCC(K))*EXP(PGC(K))
   WRITE (6,148) MM(K),SM(K),KSB(K),PCC(K)*100.,PGC(K)*100.,KS(K)
   81 CONTINUE
   32 CONTINUE
   C READING OF CHANNEL LOSS PARAMETERS
   DO 82 J=1,NC
     CL(J)=0.0
   82 CONTINUE
   QKS=0.0
   PLS=0.0
   IF (ICL.EQ.0) GO TO 33
   READ (5,113) (CL(J), J=1,NC)
   C CL = CHANNEL LOSSES IN MM/HR
   READ (5,113) PLS, QKS
   C PLS = INITIAL CHANNEL LOSS EXPRESSED AS A RATIO
   C TO THE PEAK CHANNEL DISCHARGE, (RATIO < 0.5)
   C QKS = DECAY FACTOR ( < 1.0 ) FOR REDUCING CHANNEL LOSS
   C PER UNIT TIME INTERVAL
   33 CONTINUE
   WRITE (6,149)
   DO 83 J=1,NC
     WRITE (6,150) IC(J), CL(J)
   83 CONTINUE
   WRITE (6,128) PLS, QKS
   WRITE (6,102)
   C READING OF THIESEN WEIGHTS FOR GAGES
   DO 84 J=1,NC
     READ (5,108) (WT(J,K), K=1,NG)
   C WT(J,K) = THIESEN WEIGHT OF GAGE K FOR COMPUTING
   C RAINFALL INPUT TO CELL J.
APPENDIX A. PROGRAM LISTING

28 CONTINUE
DO 55 K=1,NG
TWT(K)=0.0
DO 55 J=1,NC
TWT(K)=TWT(K)+WT(J,K)*ALF(J)
C C TWT(K)=THIessen WEIGHT OF Gage K FOR COMPUTING
C C MEAN WATERSHED RAINFALL.
C
55 CONTINUE
C
C --- READING OF STORM DATA
C NZ=0
READ (5,104) TITLE
C C C TITLE=IDENTIFICATION OF STORM EVENT
READ (5,109) KZR
C C C KZR=TIME OF START OF RAINFALL IN HRS AND MIN. (KZR SHOULD BE
C C C THE SAME FOR ALL RAIN GAGES.)
WRITE (6,135)
WRITE (6,105) TITLE
WRITE (6,119) KZR,NG
C
C --- READING OF TOTAL RAINFALL DATA FOR EACH GAGE.
C NRM=0
DO 48 K=1,NG
READ (5,115) NRG(K)
C C C NRG(K)=NUMBER OF TIME INTERVALS FOR RAINFALL INPUT TO Gage K
JG=NRG(K)
DO 49 I=1,JG
RG(K,1)=0.0
49 CONTINUE
IF (JG.GT.NRM) NRM=JG
READ (5,113) (RG(K,I), I=1,JG)
C C C RG(K,I)=VALUE OF RAINFALL INTENSITY INPUT FOR Gage K DURING
C C C I-TH TIME INTERVAL, IN MM/HR.
C IF (IRE.EQ.0) GO TO 48
C --- USING THE GREEN & AMPT INFILTRATION PROCEDURE
DO 50 I=1,JG
R(K,I)=RG(K,I)
50 CONTINUE
CALL GRNA (JG,R,DT,KS,SM,RE,K)
DO 52 I=1,JG
RE(K,I)=RE(K,I+1)
52 CONTINUE
C
C --- PRINTING RAINFALL DATA FOR EACH GAGE
WRITE (6,101)
WRITE (6,144) (MM(K),K=1,NG)
WRITE (6,101)
NPT=-1
DO 56 I=1,NG

APPENDIX A. PROGRAM LISTING

IF (NRG(I).GT.NPT)NPT=NRG(I)
56 CONTINUE
DO 53 I=1,NPT
  T=I*DT
  WRITE (6,145) T,(RG(K,I),K=1,NG)
53 CONTINUE
C ---- PRINTING RAINFALL EXCESS FOR EACH GAGE
WRITE (6,101)
WRITE (6,101)
WRITE (6,146) (MM(K),K=1,NG)
WRITE (6,101)
NPT=1
DO 57 I=1,NG
  IF (NRG(I).GT.NPT)NPT=NRG(I)
57 CONTINUE
DO 58 I=1,NPT
  T=I*DT
  WRITE (6,145) T,(RE(K,I),K=1,NG)
58 CONTINUE
C ---- PRINTING OF THEISSEN WEIGHTS FOR CELLS
WRITE (6,101)
WRITE (6,101)
WRITE (6,110)
WRITE (6,131) (MM(K),K=1,NG)
WRITE (6,101)
DO 24 J=1,NC
  WRITE (6,109) IC(J),(WT(J,K),K=1,NG)
C ---- COMPUTING RAINFALL EXCESS DATA FOR EACH CELL
AR=0.0
NRC(J)=0
SRT=0.0
DO 23 I=1,NRM
  RC(J,I)=0.0
  DO 21 K=1,NG
    RC(J,I)=RC(J,I)+WT(J,K)*RE(K,I)
    RC(J,I)=RAINFALL EXCESS FOR CELL J DURING I-TH TIME INTERVAL, IN MM/HR.
  SRT=SRT+WT(J,K)*RG(K,I)
21 CONTINUE
AR=AR+RC(J,I)
IF (RC(J,I).EQ.0.0) GO TO 23
NRC(J)=I
23 CONTINUE
REC(J)=AR*DT
C REC(J)=TOTAL RAINFALL EXCESS FOR CELL J, IN MM.
RTC(J)=SRT*DT
C RTC(J)=TOTAL RAINFALL FOR CELL J, IN MM.
APPENDIX A. PROGRAM LISTING

24 CONTINUE
WRITE (6,101)
WRITE (6,109) NZ,(TWT(K),K=1,NG)
C ---- COMPUTING AVERAGE RAINFALL EXCESS FOR AREA
C CONTRIBUTING TO OUTLET OF EACH CELL
DO 45 J=1,NC
AVR=REC(J)*ALF(J)
IT=0
DO 47 M=1,4
IT=IT+KC(J,M)
47 CONTINUE
IF (IT.EQ.0) GO TO 51
DO 41 M=1,4
MC=KC(J,M)
IF (MC.EQ.0) GO TO 41
AVR=AVR+REA(MC)*ACT(MC)
41 CONTINUE
51 REA(J)=AVR/ACT(J)
C REA(J)=AVERAGE TOTAL RAINFALL EXCESS FOR AREA
C CONTRIBUTING TO OUTLET OF CELL J, IN MM.
45 CONTINUE
IQM=0
DO 46 J=1,NC
NQC(J)=0
IF (IPT(J).EQ.3) IQM=1
DO 42 I=1,300
QC(J,I)=0.0
YC(J,I)=0.0
42 CONTINUE
46 CONTINUE
DO 43 I=1,300
Q(I)=0.0
43 CONTINUE
C ---- READING IN RUNOFF DATA WHERE AVAILABLE
IF (IQM.LT.1) GO TO 36
READ (5,115) (NQC(J),J=1,NC)
C NQC(J)=NUMBER OF TIME INTERVALS OF AVAILABLE DISCHARGE DATA
C AT OUTLET OF CELL J.
C NOTE:-- COUNTING OF TIME INTERVALS FOR RUNOFF SHOULD START
C AT THE SAME STARTING TIME (KZR) USED FOR RAINFALL.
DO 26 J=1,NC
NQJ=NQC(J)
IF (NQJ.LT.1) GO TO 26
READ (5,113) (QC(J,I),I=1,NQJ)
C QC(J,I)=VALUE OF OUTFLOW DISCHARGE AVAILABLE FOR CELL J
C AT END OF I-TH TIME INTERVAL, IN CU.M./SEC.
26 CONTINUE
APPENDIX A. PROGRAM LISTING

36  AR=0.0
    AQ=0.0
    AP=0.0
    QF=0.0
    QM=0.0
    RM=0.0
    QMX=0.0
WRITE (6,102)
WRITE (6,106)
WRITE (6,127)
NPT=NQC(NC)+1
IF (NRM.GT.NPT) NPT=NRM

C   --- COMPARING RAINFALL AND RUNOFF DATA FOR WATERSHED.
DO 40 I=1,NPT
   T=I*DT
   RR=0.0
   RP=0.0
   IF (I.GT.NRM) GO TO 54
   DO 27 K=1,NG
      RP=RP+TWT(K)*RG(K,I)
   CONTINUE
   DO 44 J=1,NC
      RR=RR+ALF(J)*RC(J,I)
   CONTINUE
44  CONTINUE
27  CONTINUE
54  AR=AR+RR*DT
    AP=AP+RP*DT
    RM=RM+RR*DT*(I-0.5)*DT
    Q(I)=QC(NC,I)*3.6/AWS
C   Q(I)=OBSERVED OUTFLOW DISCHARGE AT OUTLET OF WATERSHED
C   AT END OF I-TH TIME INTERVAL, IN MM/HR.
    AQ=AQ+(Q(I)+QF)*DT/2
    QM=QM+QF*DT*(I-0.5)*DT+(Q(I)-QF)*DT*(I-2.0/3.0)*DT/2.0
    QF=Q(I)
WRITE (6,113) T,RP,RR,QF,AP,AR,AQ
C   T = TIME IN HR.
C   RP = MEAN TOTAL RAINFALL OVER WATERSHED, IN MM/HR.
C   RR = MEAN RAINFALL EXCESS OVER WATERSHED, IN MM/HR.
C   QF = RUNOFF DISCHARGE AT OUTLET, IN MM/HR.
C   AP = CUMULATIVE MEAN WATERSHED RAINFALL, IN MM.
C   AR = CUMULATIVE MEAN WATERSHED RAINFALL EXCESS, IN MM.
C   AQ = CUMULATIVE RUNOFF AT OUTLET, IN MM.
40  CONTINUE
   RM=RM/AR
   IF (AQ.EQ.0.0) GO TO 37
    QM=QM/AQ
37  UM=QM-RM
WRITE (6,121) RM,QM,UM
APPENDIX A. PROGRAM LISTING

C \( RM = \) FIRST MOMENT OF RAINFALL HYETOGRAPH, IN HRS
C \( QM = \) FIRST MOMENT OF RUNOFF HYDROGRAPH, IN HRS
C \( UM = \) FIRST MOMENT OF UNIT HYDROGRAPH, IN HRS
WRITE (6,102)
C ---- COMPUTATION OF UNIT HYDROGRAPH FOR EACH CELL.
WRITE (6,126)
DO 19 J=1,NC
AK=AKC*SQRT(NC*ALF(J))
BK=AK*0.10
AU=0.0
UF=0.0
DO 15 I=1,199
T=I*DT
TD=T/AK
IF (TD.GT.1.5) GO TO 34
UJ=(EXP(-TD)-EXP(-T/BK))/(AK-BK)
GO TO 35
34 UJ=EXP(-TD)/(AK-BK)
35 AU=AU+(UF*UF)*DIY2
NU=I+1
UF=UF
U(J,NU)=UJ
IF (UJ.LT.0.0005.0R.AU.GT.0.9990) GO TO 17
15 CONTINUE
17 U(J,NU)=0.0
SU=AU+UF*DT/2
TZ=TDF*SLC(J)/SLM
TT=TKF*SLC(J)/SLM
WRITE (6,112) IC(J),AK,TT,TZ
DO 14 I=1,NU
U(J,I)=U(J,1)/SU
14 CONTINUE
NUC(J)=NU
19 CONTINUE
C ---- COMPUTATION OF RUNOFF DUE TO RAINFALL FOR EACH CELL.
DO 30 J=1,NC
DO 63 I=1,NRM
X(I)=0.0
63 CONTINUE
NX=NRC(J)
DO 25 I=1,NX
X(I)=RC(J,I)*DT
25 CONTINUE
NU=NUC(J)
NY=NU+NX-1
UZ=0.0
APPENDIX A. PROGRAM LISTING

IF (NY.GT.300) NY=300
AY=0.0
YF=0.0
YCM(J)=0.0
DO 20 N=1,NY
   C ---- CONVOLUTION OF RAINFALL AND UNIT HYDROGRAPH
   T=N*DT
   IB=1
   IE=N
   IF (N.GT.NU) IB=N-NU+1
   IF (N.GT.NX) IE=NX
   YN=0.0
   DO 22 I=IB,IE
      K=N+1-I
      YN=YN+X(I)*U(J,K)
   22 CONTINUE
   IF (N.LT.NX) YN=YN+UZ*X(N+1)
   NYC(J)=N
   AY=AY+(YF+YN)*DT/2
   YF=YN
   YC(J,N)=YN+ALF(J)*AWS/3.6
   C YC(J,N)=RUNOFF DUE TO RAINFALL (ONLY) ON CELL J, AT THE END OF N-TH TIME INTERVAL IN CU.M./SEC.
   IF (YCM(J).LT.YC(J,N)) YCM(J)=YC(J,N)
   IF (N.LE.NX) GO TO 20
   IF (YN.LT.0.0001) GO TO 29
   20 CONTINUE
   29 YTC(J)=AY
   30 CONTINUE
   C ---- COMPUTATION OF TOTAL RUNOFF FOR EACH CELL
   WRITE (6,151)
   DO 60 J=1,NC
      DO 61 I=1,300
         QA(I)=0.0
         QB(I)=0.0
   61 CONTINUE
   C ---- COMBINING OF UPSTREAM CELLS OUTPUT
   IT=0
   DO 13 M=1,4
      IT=IT+KC(J,M)
   13 CONTINUE
   NB=NYC(J)
   IF (IT.EQ.0) GO TO 67
   NAM=0
   DO 31 M=1,4
APPENDIX A. PROGRAM LISTING

MC=KC(J,M)
IF (MC.EQ.0) GO TO 31
NA=NYC(MC)
DO 62 I=1,NA
QA(I)=QA(I)+YC(MC,I)
62 CONTINUE
IF (NAM.LT.NA) NAM=NA
31 CONTINUE

NA=NAM
TZ=TDF*SLC(J)/SLM
TT=TKF*SLC(J)/SLM
C ---- ROUTING OF CHANNEL INPUT THROUGH CELL
CALL RUTK (DT,TZ,TT,NA,NB,QA,QB,300)
IF (NB.GT.300) NB=300
IF (ICL.EQ.0) GO TO 68

C ---- COMPUTING THE CHANNEL LOSSES FOR CELL
QCA(J)=CLE(J)*CW(J)*CL(J)/3600.
CA(J)=CLE(J)*CW(J)*1000.
C QCA(J)=CHANNEL LOSSES IN CU.M PER SECOND
C CA(J)=CHANNEL AREA OF CELL IN SQ.M.
WRITE (6,152) IC(J),CLE(J),CW(J),CA(J),CL(J),QCA(J)

C ---- SUBTRACTING CHANNEL LOSSES IN CELL
QBX=0.0
DO 59 I=1,NB
IF (QB(I).GT.QBX) QBX=QB(I)
59 CONTINUE

QMC=QCA(J)*SLC(J)/SLM
QLC=PLS*(QBX-QMC)
IF (QLC.LT.0.0) QLC=0.0
MBS=0
NBT=0
DO 65 I=1,NB
QBP=QB(I)-QMC
QB(I)=QB(I)-QMC
IF (QB(I).LT.0.0) QB(I)=0.0
IF (QB(I).GT.0.0) NBT=I
IF (QBP.LE.QLC.AND.MLS.EQ.0) GO TO 65
MBS=1
QLC=QLC*QKS
65 CONTINUE

NB=NBT
68 IF (NYC(J).GT.NB) NB=NYC(J)
IF (NB.GT.NYC(J)) NYC(J)=NB

YTM(J)=0.0
AY=0.0
YF=0.0
C ---- COMBINING RUNOFF DUE TO RAINFALL AND ROUTED CHANNEL INFLOW
APPENDIX A. PROGRAM LISTING

DO 64 I=1,NB
YC(J,I)=YC(J,I)+QB(I)
C  YC(J,I)=PREDICTED TOTAL OUTFLOW FROM CELL J AT END OF I-TH
C  TIME INTERVAL, IN CU.M./SEC.
IF (YTM(J).LT.YC(J,I)) YTM(J)=YC(J,I)
AY=AY+(YC(J,I)+YF)*DT/2
YF=YC(J,I)
64 CONTINUE
YTA(J)=AY*3.6/(ACT(J)*AWS)
60 CONTINUE
WRITE (6,102)
SRT=0.0
SYC=0.0
WRITE (6,129)
DO 69 J=1,NC
C  ---- LISTING OF RAINFALL AND PREDICTED RUNOFF FOR EACH CELL
WRITE (6,107) IC(J),RTC(J),YTC(J),REA(J),YTA(J),YCM(J),YTM(J)
C  RTC(J)=TOTAL RAINFALL FOR CELL J, IN MM.
C  YTC(J)=TOTAL RUNOFF FOR CELL J, IN MM.
C  REA(J)=TOTAL RAINFALL FOR AREA ABOVE OUTLET OF CELL J, IN MM.
C  YTA(J)=TOTAL RUNOFF FOR AREA ABOVE OUTLET OF CELL J, IN MM.
C  YCM(J)=PEAK DISCHARGE DUE TO RAIN ON CELL J, IN CU.M./SEC.
C  YTM(J)=PEAK DISCHARGE AT OUTLET OF CELL J, IN CU.M./SEC.
C  ---- AVERAGE RAINFALL AND PREDICTED RUNOFF FOR THE ENTIRE
C  WATERSHED
SRT=SRT+RTC(J)*ALF(J)
SYC=SYC+YTC(J)*ALF(J)
C  SRT=AVERAGE RAINFALL IN MM.
C  SYC=AVERAGE PREDICTED RUNOFF IN MM.
69 CONTINUE
C  ---- PRINTING AND PLOTTING OF OUTPUT DATA
DO 70 J=1,NC
IF (IPT(J).EQ.0) GO TO 70
YF=0.0
AY=0.0
QF=0.0
AQ=0.0
T=0.0
NPT=MAX0(NQC(J),NYC(J))
WRITE (6,102)
WRITE (6,136)
WRITE (6,120) IC(J)
WRITE (6,137)
WRITE (6,130)
WRITE (6,113) T,YF,AY
DO 72 I=1,NPT
T-I*DT
APPENDIX A. PROGRAM LISTING

YA(I)=YC(J,I)
AY=AY+(YA(I)+YF)*DT*1.8/(AWS*ACT(J))
YF=YA(I)
IF (IPT(J).LT.3) GO TO 74
QB(I)=QC(J,I)
AQ=AQ+(QB(I)+QF)*DT*1.8/(AWS*ACT(J))
DQY=YA(I)-QB(I)
WRITE (6,113) T,YA(I),AY,QB(I),AQ,DQY

QB-OBSERVED DISCHARGE, IN CU.M/SEC.
AY-CUMULATIVE PREDICTED RUNOFF, IN MM.
AQ-CUMULATIVE OBSERVED RUNOFF, IN MM.
DQY-DIFFERENCE BETWEEN PREDICTED AND OBSERVED DISCHARGE.
QF=QB(I)
IF (I.GT.NQC(J)) CONTINUE
GO TO 72
74 WRITE (6,113) T,YA(I),AY
QB(I)=YA(I)
72 CONTINUE
NQ=NQC(J)
IF (NQ.LT.1) GO TO 76
76 ZZ=0.0
WRITE (6,102)
IF (IPT(J).LE.1) GO TO 70
WRITE (6,120) IC(J)
CALL PLOTA(DT,NPT,QB,YA,ZZ,300)
70 CONTINUE

AYT-PREDICTED RUNOFF AT THE OUTLET OF WATERSHED, IN MM.
AQ=OBSERVED RUNOFF AT THE OUTLET OF WATERSHED, IN MM.
VAT-PREDICTED VOLUME OF RUNOFF AT WATERSHED OUTLET, IN CU.M.
VQT-OBSERVED VOLUME OF RUNOFF AT WATERSHED OUTLET, IN CU.M.
PAYT-PRECENT OF PREDICTED RUNOFF FROM OBSERVED.
PVAT-PRECENT OF PREDICTED VOLUME FROM OBSERVED.

78 YMAX=YA(1)
QMAX=QB(1)
DO 71 I=2,NPT
T=I*DT
APPENDIX A. PROGRAM LISTING

IF (YA(I).LT.YMAX) GO TO 73
YMAX=YA(I)
TTPY=T

73 IF (QB(I).LT.QMAX) GO TO 71
QMAX=QB(I)
TIPQ=T

71 CONTINUE
PTTP=(TTPQ*100/TITY)-100

C TTPY = PREDICTED TIME TO PEAK, IN HRS.
C TIPQ = OBSERVED TIME TO PEAK, IN HRS.
C PTTP = PERCENT OF PREDICTED TIME TO PEAK FROM OBSERVED.

C --- COMPUTING DEVIATION STATISTICS
C SMA = MEAN ABSOLUTE DEVIATION (DISCHARGE)
C SME = MEAN ROOT SQUARE DEVIATION (DISCHARGE)
C SWD = MEAN OF WEIGHTED ABSOLUTE DEVIATIONS (DISCHARGE)
C DMX = MAXIMUM ABSOLUTE DEVIATION (DISCHARGE)
C PDF = ABSOLUTE DEVIATION BETWEEN PEAK DISCHARGES
C NPS = NUMBER OF POSITIVE DEVIATIONS
C NNG = NUMBER OF NEGATIVE DEVIATIONS
C NZR = NUMBER OF ZERO DEVIATIONS

NQ=NQC(NC)
NP=MAX0(NQ,NY)
NPW=NQ
SME=0.0
SMA=0.0
SMY=0.0
DMX=0.0
YMX=0.0
SWD=0.0
NNG=0
NZR=0

DO 66 I=1,NP
T=I*DT
DQY=YA(I)-QB(I)
IF (I.GT.NQ) GO TO 66
IF (DQY.LT.0.0) NNG=NNG+1
IF (DQY.EQ.0.0) NZR=NZR+1
DQY=ABS(DQY)
IF (YMX.LT.YA(I)) YMX=YA(I)
IF (QMX.LT.QB(I)) QMX=QB(I)
IF (DMX.LT.DQY) DMX=DQY
IF (YMX.EQ.0) GO TO 79
PMX=(QMX*100/YMX)-100

C YMX=MAXIMUM PREDICTED DISCHARGE, IN CU.M./SEC.
C QMX=MAXIMUM OBSERVED DISCHARGE, IN CU.M./SEC.
APPENDIX A. PROGRAM LISTING

C DMX-MAXIMUM DIFFERENCES BETWEEN DISCHARGES, IN CU.M./SEC.
C PYMX-PRECENT OF MAXIMUM PREDICTED DISCHARGE FROM OBSERVED.

79 SMA=SMA+DQY
SME=SME+DQY*DQY
SMY=SMY+YA(I)
SWD=SWD+DQY
QTS=0.5*QMX
IF (QB(I).LT.QTS) GO TO 66
SWD=SWD+DQY
NPW=NPW+1
66 CONTINUE
NPT=NQ
NPS=NPT-NNG-NZR
SMA=SMA/NPT
SME= SQRT(SME/NPT)
SWD=SWD/NPW
PDF= ABS(YMX-QMX)
WRITE (6,102)
WRITE (6,142)
WRITE (6,104) TITLE
WRITE (6,143) SRT,AYT,AQT,PAYT,VAT,VQT,PVAT,YMX,QMX,PYMX,TTPY,
*TTPQ,PTTP
WRITE (6,139) SMA,SME,SWD,DMX,PDF,NPS,NNG,NZR
NPT=MAXO(NQ,NY)
WRITE (6,102)
99 STOP
C ------- FORMATS
100 FORMAT (1HL/)
101 FORMAT (2X)
102 FORMAT (/,9X,'---- #### OOOOO #### ---',/)
104 FORMAT (20A4)
105 FORMAT (2X,20A4)
106 FORMAT (5X,'RAINFALL AND RUNOFF DATA FOR THE ENTIRE WATERSHED',/,
* 4X,51(=''),/,
* 5X,'T = TIME IN HR.' ,/,
* 5X,'RP = MEAN RATE OF RAINFALL OVER THE WATERSHED, IN MM/H
  *R.',/,
* 5X,'RR = MEAN RATE OF RAINFALL EXCESS OVER THE WATERSHED,
  *IN MM/HR.' ,/,
* 5X,'QF = SPECIFIC OBSERVED DISCHARGE PER UNIT WATERSHED AR
  *EA, IN MM/HR.' ,/,
* 5X,'AP = CUMULATIVE TOTAL WATERSHED RAINFALL, IN MM.' ,/,
* 5X,'AR = CUMULATIVE WATERSHED RAINFALL EXCESS, IN MM.' ,/,
* 5X,'AQ = CUMULATIVE OBSERVED RUNOFF AT THE WATERSHED OUTLE
  *T, IN MM.' ,/)
107 FORMAT (I5,(2X,F6.3))
108 FORMAT (14F5.4)
APPENDIX A. PROGRAM LISTING

109 FORMAT (I6,10F7.3)
110 FORMAT (2X,'CELL',24X,'TISSSEN WEIGHT FOR GAGE NO.',/,2X,75('-'))
111 FORMAT (2I5,3X,4I4,2X,3F8.3)
112 FORMAT (I5,3F8.3)
113 FORMAT (9F8.4)
114 FORMAT (10F8.4)
115 FORMAT (18I4)
116 FORMAT (' ',/,3X,'IC',3X,'ID',5X,'UPSTREAM CELLS',4X,
* ' ALF CUM A LENGTH',/,2X,56('-'))
117 FORMAT (' ',/,5X,'T = TIME IN HRS.',/, 
* 5X'Y = PREDICTED DISCHARGE, IN M./HR.',/, 
* 5X'Q = OBSERVED DISCHARGE, IN M./HR.',/, 
* 5X,'T',7X,'Y',7X,'Q',5X,'(Y-Q)',/,2X,32('-'))
119 FORMAT (2X,/,5X,'ZERO TIME =',/18,/, 
* 5X,'NUMBER OF RAIN GAGES =',/6,/, 
* 5X,'T = TIME, IN HRS.',/) 
120 FORMAT (5X,'OUTPUT FOR CELL NO.',/4I4,/,4X,26('-'))
121 FORMAT (2X,/,5X,'MOMENTS OF STORM DATA',/,4X,24('-'),/
* 5X,'FIRST MOMENT OF RAINFALL HYETOGRAPH =',/F8.4,' HRS',/, 
* 5X,'FIRST MOMENT OF RUNOFF HYDROGRAPH =',/F8.4,' HRS',/, 
* 5X,'FIRST MOMENT OF UNIT HYDROGRAPH =',/F8.4,' HRS',/) 
122 FORMAT (2X,/,5X,'OUTPUT PRINTING INFORMATION',/,4X,29('='),/, 
* 5X,'CELLS WHERE OUTPUT IS REQUIRED',/,4X,33('='),/, 
* 5X,'O = NO PRINTING IS REQUIRED.',/, 
* 5X,'1 = PRINT ONLY CELL OUTPUT DATA.',/, 
* 5X,'2 = PRINT AND PLOT CELL OUTPUT DATA.',/, 
* 5X,'3 = PRINT AND PLOT CELL OUTPUT DATA AND COMPARE TO MEA 
*SURED DATA.',/) 
123 FORMAT (5X,'WATERSHED INFORMATION',/,4X,23('='),/, 
* 5X,'WATERSHED AREA =',/F9.3,' SQ.KM.',/, 
* 5X,'STREAM LENGTH =',/F9.3,' KM.',/, 
* 5X,'TIME INCREMENT =',/F7.3,' HRS') 
124 FORMAT (5X,'MODEL PARAMETERS',/,4X,18('='),/, 
* 5X,'ROUTING PARAMETER',/,4X,19('='),/, 
* 8X,'RESERVOIR COEFFICIENT =',/F7.2,' HRS',/, 
* 8X,'ROUTING COEFFICIENT =',/F7.2,' HRS',/, 
* 8X,'TIME DELAY FACTOR =',/F7.2,' HRS') 
125 FORMAT (/,5X,'INFILTRATION PARAMETERS',/,4X,25('='),/, 
* 5X,'(EFFECTIVE MATRIC POTENTIAL AND SATURATED HYDRAULIC 
CON 
*DUCTIVITY)') 
126 FORMAT (5X,'CELL PARAMETER AND ROUTING INFORMATION',/, 
* 4X,40('='),/, 
* 5X,'IC = IDENTIFYING NUMBER OF CELL.',/, 
* 5X,'AK = VALUE OF THE RESERVOIR COEFFICIENT.',/)
APPENDIX A. PROGRAM LISTING

* 5X,'TT = CHANNEL ROUTING COEFFICIENT.',/.
* 5X,'TZ = CHANNEL TIME DELAY FACTOR.',/.
* 3X,'IC',5X,'AK',6X,'TT',6X,'TZ',/.,2X,28('1-')
127 FORMAT (5X,'T',6X,'RP',6X,'RR',6X,'QF',6X,'AP',6X,'AR',6X,
  'AQ',/.,2X,55('1-'))
128 FORMAT (/,8X,'INITIAL LOSS RATIO =',F7.3,/, 
  8X,'LOSS DECAY FACTOR =',F7.3)
129 FORMAT (5X,'CELL RAINFALL, RUNOFF AND PEAK DISCHARGE',/.
  * 4X,42('1-'),/., 
  * 5X,'IC = IDENTIFYING NUMBER OF CELL.',/.
  * 5X,'RTC = TOTAL RAINFALL FOR CELL, IN MM.',/.
  * 5X,'YTC = TOTAL RUNOFF FOR CELL, IN MM.',/.
  * 5X,'REA = TOTAL RAINFALL FOR AREA ABOVE OUTLET OF CELL, IN
    MM.',/.
  * 5X,'YTA = TOTAL RUNOFF FOR AREA ABOVE OUTLET OF CELL, IN M
    M.',/.
  * 5X,'YCM = PEAK DISCHARGE DUE TO RAIN ON CELL, IN
    CU.M./SEC.
  * '1-'. 
  * 5X,'YTC = PEAK DISCHARGE AT OUTLET OF CELL, IN
    CU.M./SEC.'.
  * '/.
  * 3X,'IC',3X,'RTC',5X,'YTC',5X,'REA',5X,'YTA',5X,
  * 'YCM',5X,'YTA',/.,2X,53('1-'))
130 FORMAT (5X,'T',7X,'YA',6X,'AY',6X,'QB',6X,'AQ',6X,'AQ',6X,'DQY',/.
  * 2X,47('1-'))
131 FORMAT (5X,1017)
133 FORMAT (5X,'CELL MODEL STRUCTURE',/.,4X,22('1-'),/.
  * 5X,'NUMBER OF CELLS ',15,/, 
  * 5X,'MEAN CELL AREA ',F8.3,' SQ.KM.',/.
  * 5X,'MEAN CELL LENGTH',F7.3,' KM.',/.
  * 5X,'IC = IDENTIFYING NUMBER OF CELL.',/.
  * 5X,'ID = IDENTIFYING NUMBER OF CELL DOWNSTREAM.',/.
  * 5X,'ALF = SIZE OF CELL, RATIO TO THE AREA OF THE WAT
    ERED.',/.
  * 5X,'CUM A = CUMULATIVE AREA, RATIO TO THE AREA OF THE WAT
    ERED.',/.
  * 5X,'LENGTH = LENGTH OF STREAM, RATIO TO THE MAIN STREAM LE
    NGTH.',/)
134 FORMAT (2X,/)20X,'MEAN ABS. DEVIATION =',F7.3,' CU.M./SEC')
135 FORMAT (5X,'STORM IDENTIFICATION AND INFORMATION',/.,4X,38('1-'))
136 FORMAT (5X,'RESULTS FOR INDIVIDUAL CELLS',/.,4X,30('1-'))
137 FORMAT (5X,'T = TIME, IN HRS.',/.
  * 5X,'YA = PREDICTED DISCHARGE, IN CU.M./SEC.',/.
  * 5X,'AY = CUMULATIVE PREDICTED RUNOFF, IN MM.',/.
  * 5X,'QB = OBSERVED DISCHARGE, IN CU.M./SEC.',/.
  * 5X,'AQ = CUMULATIVE OBSERVED RUNOFF, IN MM.'/.,
APPENDIX A. PROGRAM LISTING

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* 5X,'DOY = DIFFERENCE BETWEEN PREDICTED AND OBSERVED DISCH.
*RGE, IN CU.M./SEC.','/)
139 FORMAT (/,5X,'COMPUTING DEVIATION STATISTICS:','/,'4X,33('"-"'),'/,
* 5X,'MEAN ABSOLUTE DEVIATION = ',F8.4,' CU.M./S
*EC.'/,
* 5X,'MEAN ROOT SQUARE DEVIATION = ',F8.4,' CU.M./S
*EC.'/,
* 5X,'MEAN OF WEIGHTED ABSOLUTE DEVIATION = ',F8.4,' CU.M./S
*EC.'/,
* 5X,'MAXIMUM ABSOLUTE DEVIATION = ',F8.4,' CU.M./S
*EC,'
* 5X,'ABSOLUTE DEVIATION BETWEEN PEAKS = ',F8.4,' CU.M./S
*EC',/
* 5X,'NUMBER OF POSITIVE DEVIATIONS = ',I3,',/
* 5X,'NUMBER OF NEGATIVE DEVIATIONS = ',I3,',/
* 5X,'NUMBER OF ZERO DEVIATIONS = ',I3,/)
APPENDIX A. PROGRAM LISTING

* 5X,'IC' = IDENTIFYING NUMBER OF CELL.',/,
* 5X,'CLE' = CHANNEL LENGTH, IN KM.',/,
* 5X,'CW' = CHANNEL WIDTH, IN M.',/,
* 5X,'CA' = CHANNEL AREA, IN SQ. M.',/,
* 5X,'CL' = CONSTANT CHANNEL LOSS IN MM/HR.',/,
* 5X,'QCA' = CHANNEL LOSSES IN CU.M./SEC.',/,
* / 4X,44('/'),/

152 FORMAT (5X,I2,3X,F5.3,3X,F4.1,3X,F7.1,3X,F4.1,3X,F5.3)
END
SUBROUTINE RUTK (DT,TZ,TK,NR,NQ,R,Q,NN)
DIMENSION R(NN),Q(NN)
DIMENSION QA(400)
DO 10 I=1,NN
Q(I)=0.0
10 CONTINUE
DO 12 1=1,400
QA(I)=0.0
12 CONTINUE
CR=DT/(2*TK+DT)
CQ=(2*TK-DT)/(2*TK+DT)
QM=0.0
RF=0.0
QF=0.0
DO 25 I=1,NN
IF (I.GT.NR) R(I)=0.0
QA(I)=CR*(R(I)+RF)+CQ*QF
IM=I
QF=QA(I)
RF=R(I)
IF (QF.GT.QM) QM=QF
IF (I.LT.IM) GO TO 25
QL=0.005*QM
IF (QF.LT.QL) GO TO 30
25 CONTINUE
30 TAM=IM*DT
CT=0.0
DO 20 I=1,400
NQ=I
T=I*DT
Q(I)=0.0
IF (T.LE.TZ) GO TO 20
IF (I.GE.IM) QA(I)=0.0
CT=(T-TZ)
IF (CT.GT.TAM) GO TO 22
NQ=I+1
DO 15 J=1,I
15 CONTINUE
APPENDIX A. PROGRAM LISTING

TA=J*DT
JA=J
IF (TA.GE.CT) GO TO 16
15 CONTINUE
16 JF=JA-1
QP=0.0
IF (JA.GT.1) QP=QA(JF)
Q(I)=QP+(QA(JA)-QP)*(CT-JF*DT)/DT
20 CONTINUE
22 Q(NQ)=0.0
RETURN
END

SUBROUTINE PLOTA(DT,NP,Q,Y,YZ,NN)
CHARACTER P,C,O,B,X(101),XL
DIMENSION Q(NN), Y(NN), S(11)
DATA P/'./, C/'*'/,
SU=YZ
DO 1 I=1,NP
UM=AMAX1(Q(I), Y(I))
IF (UM.GT.SU) SU=UM
1 CONTINUE
SL=ALOG10(SU)
IF (SL.LT.0.0) SL=SL-1
EM=INT(SL)+1
U=10.0**EM
U2=U/2
U5=U/5
IF (SU.LE.U2) U=U2
IF (SU.LE.U5) U=U5
U=U/100
DO 2 I=1,11
S(I)=(I-1)*10*U
2 CONTINUE
WRITE(6, 40)
WRITE(6, 41) S
DO 5 I=1,101
X(I)=B
5 CONTINUE
DO 3 I=1,11
II=(I-1)*10+1
X(II)=P
3 CONTINUE
XJ=0.0
K=INT(YZ/U+0.5)+1
XX=X(K)
X(K)=C
WRITE(6, 42)XJ,X

"
APPENDIX A. PROGRAM LISTING

```
X(K)-XK
DO 4 J=1,NP
XJ=J*DT
L=INT(Q(J)/U+0.5)+1
K=INT(Y(J)/U+0.5)+1
XL=X(L)
XK=X(K)
X(L)=0
X(K)=C
WRITE(6, 42)XJ,X
X(L)=XL
X(K)=XK
4 CONTINUE
WRITE(6, 41) S
RETURN
40 FORMAT (20X,'ABSCISSA: TIME, IN HRS.'),/
     * 20X,'ORDINATE: DISCHARGE, IN CU.M/SEC.'),/
     * 20X,' PREDICTED DISCHARGE.'),/
     * 20X,'O OBSERVED DISCHARGE.'),/
41 FORMAT (14X,11F10.3)
42 FORMAT (11X,F7.2,2X,61A1,40A1)
43 FORMAT (1H1/)
44 FORMAT (20X,61A1,40A1)
END

SUBROUTINE GRA (NF,R,DT,KS,SM,RE,K)
DIMENSION TR(300),TF(300),R(40,300),RCUM(300),F(300),FF(300),
*RE(40,300),RECUM(300),RR(300),TP(100),PT(100),RTEMP(300),SM(40)
REAL KS(40),KSM(40)
INTEGER POND

C SUBROUTINE WRITTEN INITIALLY BY J. STONE AND L. LANE.
C THIS PROGRAM CALCULATES INFILTRATION RATES AND DEPTHS FOR UNSTEADY
C RAIN USING THE GREEN AND AMPT INFILTRATION EQUATION AS MODIFIED BY
C MEIN AND LARSON. THE EQUATION HAS THE FORM :

C F = KS + KS*SM/FF
C
C KS*T = FF - SM*LN(1 + FF/SM)
C WHERE:
C F = INFILTRATION RATE (L/T)
C KS = SATURATED CONDUCTIVITY (L/T)
C SM = EFFECTIVE MATRIC POTENTIAL (L)
C FF = CUMULATIVE INFILTRATION (L)
C LN = NATURAL LOG
```

C

APPENDIX A. PROGRAM LISTING

C INPUT:
C   1. RAINFALL RATE (MILLIMETERS/HOUR)
C   2. SATURATED CONDUCTIVITY (MILLIMETERS/HOUR)
C   3. EFFECTIVE MATRIC POTENTIAL (S*M) (MILLIMETERS)
C   WHERE:
C
C     S = DIFFERENCE IN AVERAGE CAPILLARY POTENTIAL
C     BEFORE AND AFTER WETTING
C
C     M = DIFFERENCE IN AVERAGE SOIL MOISTURE
C
C
C---------------------------------------------
C
C---------------------------------------------
C
C 1. R(K,I) ............RAINFALL RATE
C 2. RCUM(I) ............ACCUMULATED RAINFALL DEPTH
C 3. F(I) .................INfiltration RATE
C 4. FF(I) ...............ACCUMULATED INFILTRATION DEPTH
C 5. RE(K,I) .............RAINFALL EXCESS RATE
C 6. RECUM(I) ............ACCUMULATED RAINFALL EXCESS DEPTH
C 7. CU ..................INDICATOR OF PONDING IF NO PONDING AT BEGINNING
C     CU < 0 - NO PONDING   CU > 0 - PONDING
C 8. CP ..................INDICATOR OF PONDING WHEN PONDED AT BEGINNING
C     CP < 0 - PONDING STOPS DURING INTERVAL   CP > 0 - PONDING
C 9. TR(I) ...............RAINFALL TIMES
C 10. TP .................TIME OF PONDING
C 11. TS ..................PSEUDOTIME TO ADJUST REAL TIME FOR INFILTRATION
C 12. T ..................REAL TIME = TR(I)-TP+TS
C 13. PT .................ACCUMULATED RAINFALL AT TIME OF PONDING
C 14. RR(I) ..............RAINFALL DEPTH
C---------------------------------------------
C
C POND=0
C FSUM=0.0
C KK=1
C FF(1)=0.0
C RECUM(1)=0.0
C RCUM(1)=0.0
C RTEMP(1)=R(K,1)
C IT=0
C INSERT=1
C TR(1)=0
C RR(1)=0
C KSM(K)=KS(K)*SM(K)
C
C START RUN
C
C DO 20 I=2,NF
C KK=KK+1
C
APPENDIX A. PROGRAM LISTING

TR(I) = TR(I-1) + DT
RR(I) = RR(I-1) + R(K,I-1) * DT

C
C CHECK IF THERE IS PONDING IN PREVIOUS INTERVAL

C IF (POND.EQ.0) THEN

C CASE ONE: NO PONDING IN PREVIOUS INTERVAL

C IF (R(K,I-1).LE.KS(K)) THEN
    IF (R(K,I-1).EQ.0.0) THEN
        FF(KK) = FSUM
        RECUM(KK) = RECUM(KK-1)
        RCUM(KK) = RR(I)
        RTEMP(KK) = R(K,I)
        TF(KK) = TR(I)
        POND = 0
        GO TO 20
    ELSE
        FSUM = RR(I) - RECUM(KK-1)
        FF(KK) = FSUM
        RECUM(KK) = RECUM(KK-1)
        RCUM(KK) = RR(I)
        RTEMP(KK) = R(K,I)
        TF(KK) = TR(I)
        POND = 0
        GO TO 20
    ENDIF
ENDIF

C PONDING INDICATOR WHEN NO PONDING IN PREVIOUS INTERVAL

C CU = RR(I) - RECUM(KK-1) - KSM(K)/(R(K,I-1) - KS(K))

C CASE ONE-A: NO PONDING

C IF (CU.LE.0.0) THEN
    FSUM = RR(I) - RECUM(KK-1)
    FF(KK) = FSUM
    RECUM(KK) = RECUM(KK-1)
    RCUM(KK) = RR(I)
    RTEMP(KK) = R(K,I)
    TF(KK) = TR(I)
    POND = 0
    GO TO 20
ENDIF
APPENDIX A. PROGRAM LISTING

CASE ONE-B: PONDING - GET TIME TO PONDING, TP

POND=1
INSERT=1
IT=IT+1
TP(IT)=(KSM(K)/(R(K,I-1)-KS(K))-RR(I-1)+RECUM(KK-1))/
*R(K,I-1)+TR(I-1)
IF (TP(IT).LE.TR(I-1)) THEN
  TP(IT)=TR(I-1)
  INSERT=0
ENDIF
IF(INSERT.EQ.0) GO TO 10
FF(KK)=FF(KK-1)+R(K,I-1)*(TP(IT)-TR(I-1))
RECUM(KK)=RECUM(KK-1)
PT(IT)=RR(I-1)+(TP(IT)-TR(I-1))*R(K,I-1)
RCUM(KK)=PT(IT)
RTEMP(KK)=R(K,I)
TF(KK)=TP(IT)
KK=KK+1
CONTINUE

10 CUMULATIVE RAINFALL, PT, AT TIME TO PONDING, TP

IF(INSERT.EQ.0) PT(IT)=RR(I-1)

PSEUDOTIME - GET TIME SHIFT DUE TO INFILTRATION, TS

XX=(PT(IT)-RECUM(I-1))/SM(K)
TS=SM(K)/KS(K)*(XX-DLOG(1.D0+XX))

REAL TIME, T

TT=TR(I)-TP(IT)+TS

CUMULATIVE INFILTRATION, NEWTONS METHOD

CALL NEWTON (TT,FF(KK-1),FF(KK),SM,KS,K)

RECUM(KK)=RR(I)-FF(KK)
RCUM(KK)=RR(I)
RTEMP(KK)=R(K,I)
TF(KK)=TR(I)

ELSE

CASE TWO: PONDING IN PREVIOUS INTERVAL


APPENDIX A. PROGRAM LISTING

TT = TR(I) - TP(IT) + TS
CALL NEWTON (TT, FF(KK-1), FF(KK), SM, KS, K)

C CHECK IF NO PONDING BEFORE END OF INTERVAL
C
CP = RR(I) - FF(KK) - RECUM(KK-1)

C CASE TWO-A: NO PONDING BEFORE END OF INTERVAL
C
IF (CP < 0.0) THEN
    FF(KK) = RR(I) - RECUM(KK-1)
    FSUM = FF(KK)
    RECUM(KK) = RECUM(KK-1)
    RCUM(KK) = RR(I)
    RTEMP(KK) = R(K, I)
    TF(KK) = TR(I)
    POND = 0
ELSE
C CASE TWO-B: PONDING CONTINUES MERRILY ON
C
    RECUM(KK) = RR(I) - FF(KK)
    RCUM(KK) = RR(I)
    RTEMP(KK) = R(K, I)
    TF(KK) = TR(I)
ENDIF
IF (POND.EQ.0) GO TO 20
ENDIF

20 CONTINUE
IF (RECUM(NF).EQ.0) RETURN
NS = KK
DO 30 I = 1, NS - 1
    DTIME = TF(I+1) - TF(I)
    F(I) = (FF(I+1) - FF(I))/DTIME
    IF (F(I).LT.0.0) F(I) = 0.0
    R(K, I) = RTEMP(I)
    RE(K, I) = (RECUM(I+1) - RECUM(I))/DTIME
    IF (RE(K, I).LT.0.0) RE(K, I) = 0.0
    IF (I.EQ.1) REMAX = RE(K, I)
    IF (RE(K, I).GT.REMAX) THEN
        NM = I
        REMAX = RE(K, I)
    ENDIF
    IF (RE(K, I).GT.0.0) NT = I
30 CONTINUE
F(NS) = 0.0
RE(K, NS) = 0.0
SUBROUTINE NEWTON (TIME,FFPAST,FFNOW,SM,KS,K)
REAL KS(40)
DIMENSION SM(40)
DOUBLE PRECISION NU1,DE1,TEST

YY=0.10
IF (FFPAST.NE.0.0) YY=FFPAST
10 NU1=TIME*KS(K)-(YY-SM(K)*ALOG(1.0+YY/SM(K)))
DE1=YY/(SM(K)+YY)
TEST=NU1/DE1
XX=YY+TEST
IF (ABS(TEST).GT.0.0001) THEN
   YY=XX
   GO TO 10
ENDIF
FFNOW=YY
RETURN
END
Appendix B

HYDROGRAPH PLOTTING
APPENDIX B. HYDROGRAPH PLOTTING

WATERSHED 11
JULY 30, 1966 (1)

---

**DISCHARGE (c.u.m./s.)**

**TIME (hr.)**

---

- **PREDICTED**
- **OBSERVED**
- **FORECASTED**
APPENDIX B. HYDROGRAPH PLOTTING

WATERSHED 11
AUG. 5, 1966 (2)

DISCHARGE (cu.m./s.)

PREDICTED
OBSERVED
FORECASTED

TIME (hr.)
WATERSHED 11
JULY 7, 1967 (3)

- PREDICTED
- OBSERVED
- FORECASTED
APPENDIX B. HYDROGRAPH PLOTTING

WATERSHED 11
SEPT. 10, 1967 (4)

- PREDICTED
- OBSERVED
- FORECASTED

DISCHARGE (cu.m./s.)

0.00 10.00 20.00 30.00 40.00 50.00

0.00 2.00 4.00 6.00 8.00

TIME (hr.)
APPENDIX B. HYDROGRAPH PLOTTING

WATERSHED 11
AUG. 5, 1968 (5)

- - - PREDICTED
- - OBSERVED
- FORECASTED
WATERSHED 11
AUG. 12, 1971 (6)

--- PREDICTED
-- OBSERVED
- - FORECASTED
WATERSHED 11
AUG. 18, 1971 (7)

PREDICTED  -  OBSERVED  -  FORECASTED
APPENDIX B. HYDROGRAPH PLOTTING

WATERSHED 11
AUG. 18, 1971 (8)

- PREDICTED
- OBSERVED
- FORECASTED

DISCHARGE (cum. m/s)

TIME (hr.)
WATERSHED 11
JULY 12, 1973 (9)

---

APPENDIX B. HYDROGRAPH PLOTTING
WATERSHED 11
JULY 15, 1973 (10)

- PREDICTED
- OBSERVED
- FORECASTED
APPENDIX B. HYDROGRAPH PLOTTING

WATERSHED 11
AUG. 22, 1975 (11)

---

PREDICTED

OBSERVED

FORECASTED

TIME (hr.)

DISCHARGE (cu. m./s.)
APPENDIX B. HYDROGRAPH PLOTTING
WATERSHED 11
JULY 27, 1976 (13)

---
PREDICTED
---
OBSERVED
---
FORECASTED

APPENDIX B. HYDROGRAPH PLOTTING
APPENDIX B. HYDROGRAPH PLOTTING

WATERSHED 11
JUNE 14, 1977 (14)

- PREDICTED
- OBSERVED
- FORECASTED
APPENDIX B. HYDROGRAPH PLOTTING

WATERSHED 11
JULY 31, 1977 (15)

- - PREDICTED
- - OBSERVED
- - FORECASTED

DISCHARGE (cu.m/s.)

TIME (hr.)
APPENDIX B. HYDROGRAPH PLOTTING

WATERSHED 11
AUG. 15, 1977 (16)

- - - - -
PREDICTED

- -
OBSERVED

- - -
FORECASTED
WATERSHED 11
SEPT. 1, 1977 (17)

---
PREDICTED

OBSERVED

FORECASTED
APPENDIX B. HYDROGRAPH PLOTTING
APPENDIX B. HYDROGRAPH PLOTTING
APPENDIX B. HYDROGRAPH PLOTTING
# Appenix B. Hydrograph Plotting

**Watershed 11**
**Sept. 11, 1982 (21)**

<table>
<thead>
<tr>
<th>Time (hr.)</th>
<th>Predicted</th>
<th>Observed</th>
<th>Forecasted</th>
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![Graph showing discharge over time for Watershed 11 on Sept. 11, 1982 with predicted, observed, and forecasted lines.](image-url)
APPENDIX B. HYDROGRAPH PLOTTING

WATERSHED 8
SEPT. 10, 1967 (4)

PREDICTED
OBSERVED
FORECASTED

DISCHARGE (cu.m./s.)

TIME (hr.)
APPENDIX B. HYDROGRAPH PLOTTING

WATERSHED 8
JULY 27, 1976 (13)

- - - - PREDICTED
- - - - OBSERVED
- - - - FORECASTED

DISCHARGE (cu.m./s.)

TIME (hr.)
APPENDIX B. HYDROGRAPH PLOTTING

WATERSHED 8
JUNE 14, 1977 (14)

- - - PREDICTED
- - OBSERVED
- - - FORECASTED
WATERSHED 8
JULY 31, 1977 (15)

- PREDICTED
- OBSERVED
- FORECASTED

APPENDIX B. HYDROGRAPH PLOTTING
APPENDIX B. HYDROGRAPH PLOTTING

WATERSHED 8
AUG. 1, 1978 (18)

- - - PREDICTED
- - - OBSERVED
- - FORECASTED

DISCHARGE (cu.m./s.)

TIME (hr.)
WATERSHED 8
AUG. 4, 1980 (19)

- PREDICTED
- OBSERVED
- FORECASTED
References Cited


REFERENCES CITED


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