CASC2D USER'S MANUAL

A TWO-DIMENSIONAL WATERSHED RAINFALL-RUNOFF MODEL

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Acknowledgements

1. INTRODUCTION

Physically-based, distributed computer modeling of rainfall-runoff processes in watershed hydrology has gained considerable attention in recent years. Analysis of the processes controlling the watershed response typically requires solution of fundamental partial differential equations for overland flow and channel flow. However, analytical solutions have not been found except for very simplified cases. These solutions are further complicated by the temporal variations introduced by transient nature of rainfall events and infiltration processes. The inability to obtain general analytical solutions has resulted in the adoption of various numerical schemes to simulate rainfall-runoff events using high speed computers.

The first step in simulating a rainfall-runoff event on a watershed is to determine the excess rainfall. This step requires the adoption of an infiltration scheme which can predict the portion of the rainfall that drains into the ground. Such a scheme must accommodate both spatial variations due to soil texture changes, and temporal variations due to time-variant nature of both rainfall and soil infiltration capacity. Additionally, the fact that rainfall history affects the infiltration rate at the present time, has to be accounted for in the infiltration scheme. Ideally the scheme should also rely on physically measurable soil infiltration parameters. The Green-Ampt infiltration equation adequately satisfies these requirements and is therefore well-suited for distributed watershed modeling.

Once infiltration is accounted for, the excess rainfall can accumulate as surface water and begin to flow. This overland flow is generally a two-dimensional process which is controlled by spatial variations in slope, surface roughness, excess rainfall, and other parameters. Solutions for the full dynamic momentum equation for overland flow are complicated and generally unnecessary for most watershed conditions. Hence a diffusive wave approximation is preferred.

As the overland flow drains into stream channels, one dimensional flow prevails. The diffusive wave equation for channel flow can predict the possible backwater effects in main channels and tributaries. As in the other watershed processes, the spatial variations in channel parameters must be accounted for in the model.

Based on the watershed processes that have been discussed, this model, CASC2D has been developed to determine the runoff hydrograph generated from any temporally-spatially varied rainfall event. The main objective of this model has been to provide a research tool for further analysis of temporal and spatial variations. It can further be used for real-time forecasting of rainfall-runoff events. The dynamic graphics capability of the model provides additional insights into the physical processes and their distribution in time and space.

2. GOVERNING EQUATIONS

2.1. Infiltration

The Green-Ampt infiltration scheme has gained considerable attention in the past decade (Philip, 1983), partially due to ever growing trend towards physically-based hydrologic modeling. The parameters of the Green-Ampt equation are based on the physical characteristics of the soil and therefore can be determined by field measurements or experiments. The Green-Ampt equation may be written as :

$$f = K_s \left(1 + \frac{H_f M_d}{F} \right)$$

where f = infiltration rate
K_s = hydraulic conductivity at normal saturation
H_f = capillary pressure head at the wetting front
M_d = soil moisture deficit equal to $(\theta_e - \theta_i)$
θ_e = effective porosity equal to $(\varphi - \theta_r)$
φ = total soil porosity
θ_r = residual saturation
θ_i = soil initial moisture content
F = total infiltrated depth

The head due to surface depth has been neglected as H_f easily overpowers shallow overland depth. Rawls et al. (1983) provided sets of average values of total porosity, effective porosity, capillary pressure head, and hydraulic conductivity based on soil texture class (see Table 1 on page 5).

2.2. Overland Flow

The Saint-Venant equations of continuity and momentum describe the mechanics of overland flow. The two-dimensional continuity equation in partial differential form reads as :

$$\frac{\partial h}{\partial t} + \frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y} = e$$

where h = surface flow depth
q_x = unit flow rate in x-direction
q_y = unit flow rate in y-direction
e = excess rainfall equal to (i-f)
i = rainfall intensity

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f = infiltration rate
x,y = cartesian spatial coordinates
t = time

The momentum equation in the x and y directions may be derived by equating the net forces per unit mass in each direction to the acceleration of flow in the same direction. The two-dimensional form of equations of motion are :

$$\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} = g \left(S_{0x} - S_{fx} - \frac{\partial h}{\partial x} \right)$$

$$\frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} = g \left(S_{0y} - S_{fy} - \frac{\partial h}{\partial y} \right)$$

where u,v = average velocities in x and y directions, respectively
S_{0x}, S_{0y} = bed slopes in x and y directions, respectively
S_{fx}, S_{fy} = friction slopes in x and y directions, respectively
g = acceleration due to gravity

The right hand side of the momentum equations describes the net forces along the x and y directions while the left hand side represents the local and convective acceleration terms.

In simplifying the momentum equations, the kinematic wave approximation assumes that all terms, except the bed slope and the friction slope, are negligible. This assumption, which is particularly valid for steep bed slopes, has been the basis for many rainfall- runoff models. Kinematic wave, however, can't predict backwater effects due to downstream disturbances that may be important when simulating floods (Beven, 1985). On the other hand, diffusive wave can simulate backwater effects and is considered to be applicable for overland flow over rough surfaces and for channel flows. The momentum equation based on the diffusive wave approximation reduces to

$$S_{fx} = S_{0x} - \frac{\partial h}{\partial x}$$

From the three equations of continuity and momentum, five hydraulic variables need to be determined. Therefore a resistance law should be established to relate flow rate to depth and to other parameters. A general depth-discharge relationship may be written, in the x-direction for example, as :

$$q_x = \alpha_x h^\beta$$

where α_x and β are parameters which depend on flow regime; i.e. laminar or turbulent. For laminar flow in x-direction, we have

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$$\alpha_x = \frac{8g}{K\nu} S_{fx} \quad ; \quad \beta = 3$$

where K = resistance coefficient, and ν = kinematic viscosity. Similarly, for turbulent flow over a rough boundary, the Manning empirical resistance equation is used :

$$\alpha_x = \frac{S_{fx}^{1/2}}{n} \quad ; \quad \beta = 5/3$$

where n = Manning roughness coefficient.

2.3. Channel Flow

A one dimensional diffusive channel flow equation has been incorporated into the model. The governing equations are similar to those of overland flow except for a finite width. The one dimensional equation of continuity reads as follows :

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = q_l$$

where A = channel flow cross-section
Q = total discharge in the channel
q_l = lateral inflow rate per unit length, into or out of the channel

Most cases of channel flow occur in the turbulent flow regime. The following equation represents the application of Manning's resistance equation to channel flow.

$$Q = \frac{1}{n} A R^{2/3} S_f^{1/2}$$

where R = hydraulic radius
S_f = friction slope

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Table 1. Green-Ampt Parameters based on Soil Texture

Soil Texture	Total Porosity	Effective Porosity	Wetted Front Capillary Head (cm)	Hydraulic Conductivity (cm/h)
sand	0.437	0.417	4.95	11.78
loamy sand	0.437	0.401	6.13	2.99
sandy loam	0.453	0.412	11.01	1.09
loam	0.463	0.434	8.89	0.34
silt loam	0.501	0.486	16.68	0.65
sandy clay loam	0.398	0.330	21.85	0.15
clay loam	0.464	0.309	20.88	0.10
silty clay loam	0.471	0.432	27.3	0.10
sandy clay	0.430	0.321	23.90	0.06
silty clay	0.479	0.423	29.22	0.05
clay	0.475	0.385	31.63	0.03

3.MODEL FORMULATION

3.1. General Technique

The two dimensional explicit numerical solution has been selected to simulate the overland flow. The watershed under analysis is considered to be a solution domain digitized by a square grid mesh of predetermined size, W. The soil characteristics, for instance roughness and soil infiltration parameters, are assumed uniform throughout each square element. These characteristics, however, can vary from one element to another due to the distributed nature of the model. Nodal values of hydraulic variables, such as depth, are taken at the center of each element. **Fig.** 1 illustrates a typical two dimensional finite difference grid mesh of 9 square elements which can be imposed on part of a watershed.
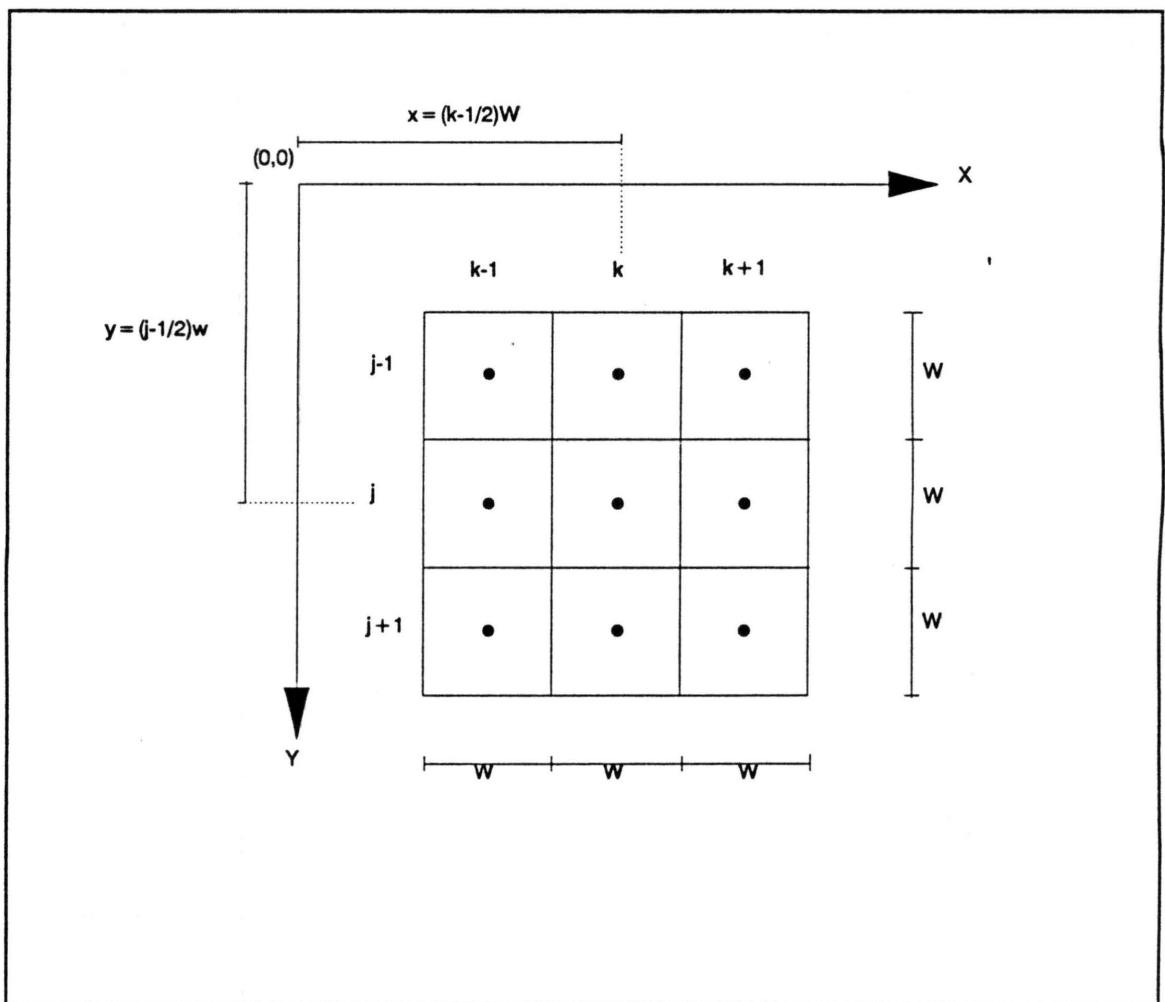

Figure 1. A Typical Two Dimensional Model Grid Mesh

Each element is identified by its row (j) and column (k) numbers. A shape matrix determines the overall shape of the watershed domain with the number 1

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implying an existing element within the watershed and the number 0 a non-existing one (outside the watershed boundary). Any element with 0 in shape matrix (ISHP) stays out of model's internal calculations.

3.2. Infiltration

Before routing the overland flow for each time step, the infiltration component is subtracted from the surface water depth at the beginning of the time step. Based on the total accumulated infiltration depth into the soil up to the current time step, the capacity infiltration rate for each square element in the watershed is computed and compared to the existing surface depth. This depth divided by the time step, is a measure of the maximum rate that can be infiltrated. If the capacity exceeds the maximum rate, then the entire surface depth infiltrates over the current time step. Otherwise, the surface depth is only reduced by the capacity infiltration rate multiplied by the time step. The infiltration capacity in the model is determined for the middle of the time step as follows :

$$f^{t+\Delta t} = K_s [1 + \frac{H_f M_d}{F^t + \frac{\Delta t}{2} f^{t+\Delta t}}]$$

Solving the above equation for $f^{t+\Delta t}$ yields :

$$f^{t+\Delta t} = \frac{1}{2 \Delta t} [P_1 + (P_1^2 + 8 P_2 \Delta t)^{1/2}]$$

where P_1 = a parameter equal to $(K_s \Delta t - 2F^t)$
P_2 = a parameter equal to $(K_s F^t + K_s H_f M_d)$

The infiltration calculation is performed for all elements depending on the soil type and the corresponding infiltration parameters in each element.

3.3. Overland Flow Routing

According to the mass conservation principle (continuity equation) for an incompressible fluid, the net amount of mass (volume) entering an element over a short period of time is proportional to the change in mass (volume) within the element. Application of a first order approximation to the continuity equation for element (j,k) results in :

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$$h^{t+\Delta t}(j,k) = h^t(j,k) + \bar{e}\,\Delta t - [\frac{q_x^t(k\to k+1) - q_x^t(k-1\to k)}{W}]\,\Delta t - [\frac{q_y^t(j\to j+1) - q_y^t(j-1\to j)}{W}]\,\Delta t$$

where $h^{t+\Delta t}(j,k)$ = flow depth at element (j,k) at time $t + \Delta t$

$h^t(j,k)$ = flow depth at element (j,k) at time t

Δt = time step duration

$\bar{e}$ = average excess rainfall rate over one time step beginning from time t

$q_x^t(k\to k+1)$, $q_x^t(k-1\to k)$ = unit flow rates in x-direction at time t, between (j,k) and (j,k + 1), and (j,k-1) and (j,k), respectively

$q_y^t(j\to j+1)$, $q_y^t(j-1\to j)$ = unit flow rates in y-direction at time t, between (j,k) and (j + 1,k), and (j-1,k) and (j,k), respectively

W = square element size

The unit flow rate at any position and any time depends solely on the flow direction, which is determined by the sign of the friction slope. For example, in the x-direction, first the diffusive friction slope is computed as :

$$S_{fx}^t(k-1\to k) = S_{0x}(k-1\to k) - \frac{h^t(j,k) - h^t(j,k-1)}{W}$$

in which bed slope is given by :

$$S_{0x}(k-1\to k) = \frac{E(j,k) - E(j,k-1)}{W}$$

where E represents the surface ground elevation at the center of the square element, and the arrows imply the direction. Based on the calculated friction slope, the turbulent flow rate is closely approximated by :

$$q_x^t(k-1\to k) = \frac{1}{n(j,k-1)}\,[h^t(j,k-1)]^{5/3}\,[S_{fx}^t(k-1\to k)]^{1/2} \quad \text{if} \quad S_{fx}^t(k-1\to k) \geq 0$$

$$q_x^t(k-1\to k) = -\frac{1}{n(j,k)}\,[h^t(j,k)]^{5/3}\,[-S_{fx}^t(k-1\to k)]^{1/2} \quad \text{if} \quad S_{fx}^t(k-1\to k) < 0$$

Similarly, the discharge $q_x^t(k\to k+1)$ is calculated based on the sign of $S_{fx}^t(k\to k+1)$. The flow rates in the y-direction are calculated based on the sign of the friction slopes in the y-direction. The initial condition for surface depth is assumed to be zero but it may easily be modified within the program, if necessary. The boundary condition is accounted for by having no inflow to the elements at the periphery of the watershed. The solution advances through time until it reaches the user's specified termination time.

3.4. Channel Flow Routing

A one-dimensional channel routing, based on diffusive wave similar in principle to the overland flow routing, has been formulated in the model. For each time step, infiltration and overland flow routing are processed. This determines the net rate of overland flow pouring into the channel elements. Each individual channel, with constant properties, is routed towards junctions, if any, and ultimately towards the watershed outlet. Prior to the model execution, all channels must be ordered with respect to variations in width, depth, and roughness. Any given channel path, identified by a series of elements through which it passes, must have a constant width, depth, and roughness.

The channel cross section is assumed to be rectangular, and, if straight, it lies in the middle of square channel element (Fig. 2). If the channel changes direction within a certain element, it runs from the middle of the entering side to the center of the element and then to the middle of the exiting side.
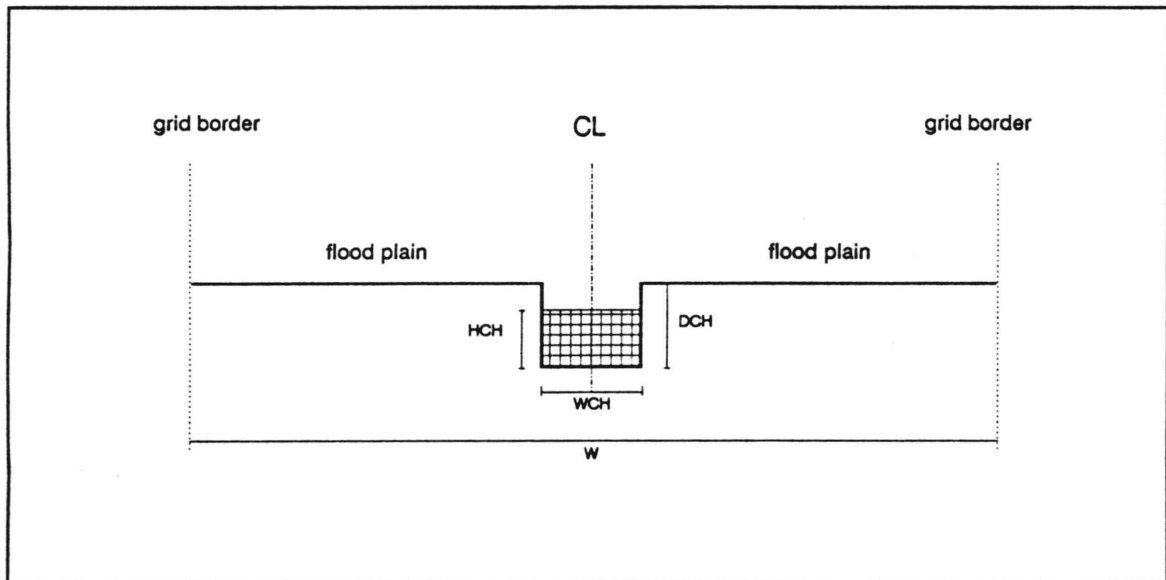
Figure 2. Channel Cross Section

In special cases, the channel may flow over into the floodplain, in which case the floodplain will be treated as part of the overland plain. Therefore, for each channel element, there can be channel flow restricted to the channel width and an overland flow when overflow from the channel occurs.

Backwater effects can be properly handled, even at the junctions of tributary channels. In the model formulation, the channel cross section is not subject to infiltration, which is likely to be negligible compared to the flow rate in the channel. However, any overland flow running toward the channel, channel overflow, and any specified detention storage all remain subject to infiltration. The details of data preparation for channels will be explained in Section 5.1.

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4.MODEL OPTIONS

There are several user's options that may be activated based on specific conditions. These options include detention storage, raingages for non-uniform rainfall, and graphics display.

4.1. Detention Storage

Specifying a detention depth value, SDEP, causes overland surface water to be accumulated until it reaches that value at which point it starts flowing. Clearly, the detention depth increases the infiltrated volume of water. Wherever microscale soil topography demands water being stored before it can flow, a detention storage proportional to the average height of those microscale variations may better reflect the physics of overland processes.

Another important application of detention storage is where vegetated areas are present. Based on the type of vegetation, a detention depth may be specified to compensate for the increased chance of infiltration before surface water reaches the given depth. In such a case, a higher value of Manning's n is also justified.

4.2. Raingages

A model parameter, called IRAIN, determines which type of rainfall data is being simulated. When analyzing rainfall data (IRAIN = 1), an interpolation scheme based on the inverse distance squared approximates the distribution of rainfall intensity over the watershed :

$$i^t(j,k) = \frac{\sum_{m=1}^{NRG} \dfrac{i^t_m(jrg,krg)}{d^2_m}}{\sum_{m=1}^{NRG} \dfrac{1}{d^2_m}}$$

where $i^t(j,k)$ = rainfall intensity in element (j,k) at time t
$i_m t(jrg,krg)$ = rainfall intensity recorded by m-th raingages located at (jrg,krg) at time t
d_m = distance from element (j,k) to m-th raingage located at (jrg,krg)
NRG = total number of recording raingages

If no raingage data is available, rainfall is assumed to be uniform over the watershed by specifying the IRAIN parameter as 0.

4.3. Graphics Display

When desired, the model provides graphical displays on either CGA or VGA monitors. Elevation and soil type maps can be pictured by specifying IELPLT and ISOILPLT as 1. The dynamic window ,displaying rainfall intensity, surface depth, and accumulated infiltration depth, may be activated when IDEPPLT is 1. The dynamic window is updated each NPLT time step. A display of the progressive runoff hydrograph at the watershed outlet can be observed on the same screen. The graphics routine must be adjusted for different watersheds.

5.MODEL REQUIREMENTS

5.1. Input Data

Before executing the model, several datafiles must be prepared. There are 7 major datafiles : SHAP.DAT, ELAVG.DAT, RAIN.DAT, IMAN.DAT, SOIL.DAT, CHN.DAT, and DATA1. The first 6 require specific data and the last file provides the general parameters. The list of variables and their location in the datafiles is as follows.:

1. ISHP : This is a (M×N) matrix, where M is the total number of rows and N is the total number of columns. ISHP determines the shape of the watershed. A square grid mesh of size W is first superimposed on the watershed map. The grid size is selected by the user based upon desired accuracy and simulation time. The grid size also limits the length of the time step. Highly irregular watersheds or watersheds with large variations in topography, soil type, roughness, and vegetation cover require the use of a small grid size.

After overlying the mesh, each grid (j,k) must be checked to see if it covers part of the watershed or lies outside the watershed boundaries. If it lies within, the user must put a 1 in ISHP(j,k), or a 0 if it lies outside. The sequence of 1s and 0s, starting from row 1 to row M, is assembled in the datafile SHAP.DAT with the data entered in a single column. ISHP is read with the following format :

```
      DO 1 j = 1,M
        DO 1 k = 1,N
          READ(25,*) ISHP(j,k)
1         CONTINUE
```

where 25 is the unit number for SHAP.DAT.

It is important to note that ISHP(j,k) is changed within the model if any channel passes through element (j,k). The changes, however, is not stored.

2. E : This is a (M×N) matrix, stored in the datafile ELAVG.DAT with the same format (ordered in a single column) as ISHP, which contains the elevations of the grid cell centers. Only elevations for those grids with ISHP equal to 1 (inside the watershed) must be prepared. The following format has been inserted inside the loop DO 1 (mentioned above) :

```
      ..........
        IF(ISHP(j,k).EQ.1) READ(26,*) E(j,k)
      ..........
```

For channel elements the elevation of their floodplain not the channel bottom, must be input.

3. IMAN : This is a (M×N) integer matrix carrying the Manning n code number for each grid. Based on roughness characteristics of the surfaces in the watershed, values of surface roughness are first grouped (NMAN = number of surface roughness groups). Each group of surface roughness then has a constant Manning n roughness parameter value as used in Manning equation. Every grid element, at (j,k) for example, is dominated by a certain surface roughness type, whose group number (code) is stored in IMAN(j,k). IMAN is read in a manner similar to E; that is if ISHP(j,k) equals 1, IMAN is read from the datafile IMAN.DAT.

If the watershed is assumed to be well represented by a single roughness value, then NMAN must be specified as 1 and no IMAN.DAT datafile is needed.

4. ISOIL : This is another (M×N) matrix carrying the soil group number, or soil code, for each grid cell. Based upon the infiltration characteristics of the soils in the watershed, the soils are first grouped (NSOIL = number of soil groups). Each group of soils has constant infiltration parameters as used in the Green-Ampt infiltration equation. Every grid element, at (j,k) for example, is occupied by a dominating soil group. The corresponding soil group number (code) is stored ISOIL(j,k). ISOIL is read in a similar manner to E; that is if ISHP(j,k) equals 1 then ISOIL is read from the datafile SOIL.DAT.

If the watershed is assumed to contain only one soil, then NSOIL must be specified as 1 and no SOIL.DAT datafile is needed.

5. ICHN : This is a three dimensional (NCHN×MAXCHN×2) matrix containing the channel element addresses in which 2 is for row and column numbers. For the model, NCHN represents the total number of channels being considered and MAXCHN is a user selected value indicating the maximum length of any single channel, throughout the channel network system, as determined by the number of elements through which the channel passes. MAXCHN is determined, rather arbitrarily, based on amount of variations in channel orders, the locations of junctions, the average length of channels within various orders, and also the optimum matrix size for ICHN. The ideal case would be such that all channels have a length equal to MAXCHN minus 1. The number of channel orders is affected by any changes in the channel parameters including width, depth, and Manning n. In the model, however, a single channel in any order may have to be divided into several channels if the original length exceeds MAXCHN minus 1 (see section 5.2. for an example).

Once MAXCHN is set, the number of channels, NCHN, may be determined by following the path of each channel. If, for example, channel #6 has a length of 12×W and pours into the next channel (say channel #7), the 13-th positions in ICHN, (6,13,1), and (6,13,2), are filled with two negative numbers such as -1. Those negative numbers indicate that the last channel element in channel #6 will be the beginning element of another channel (here #7). Note that for this particular example, MAXCHN must be equal to 13, or greater if any other channel is longer than channel #6. This process is done for all the channels until the last channel reaches the outlet.

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A junction is simply a channel element at which a minimum of one and a maximum of three channels, with either different channel parameters or similar ones, join together. Note again that if a given prismatic channel, channel A for example, in the watershed is so long that it exceeds the predetermined value of MAXCHN minus 1, then is must be broken up into a number of channels (A1, A2, A3, etc), such that neither channel, in length, exceeds MAXCHN minus 1. As such, the last element along each channel is considered to be a junction, joining the current channel to the next. In the channel datafile, CHN.DAT, junctions are marked by a negative number following their address.

6. PMAN : This is a vector of size NMAN containing all the Manning roughness coefficients, corresponding to each roughness group existing in the watershed. PMAN is read from the DATA1 datafile.

7. PINF : This is a (NSOIL×3) matrix containing infiltration parameters. Hydraulic conductivity, capillary suction head, and soil moisture deficit occupy the first, second, and third columns of PINF, respectively. If soil moisture values varies even for a single soil, then NSOIL must be increased accordingly. The first two soil infiltration parameters may be measured experimentally, or estimated from Table 1 in Section 2.3. The initial moisture, however, must be known from field studies.

8. CHP : This is a (NCHN×3) matrix containing the channel parameters. Channel width, depth, and Manning n roughness coefficient take up the first, second and last columns of CHP, respectively. The CHP data is placed at the top of the CHN.DAT datafile.

9. XRG & YRG : These are two vectors of size NRG (number of raingages) to designate column and row numbers (addresses) of any raingages installed in the watershed. NRG, XRG, and YRG are read from DATA1.

10. RRG : This is a ((NITRN/NREAD)×NRG) matrix to define the rainfall intensities as recorded by raingages. NITRN denotes the total number of time steps in rainfall duration, and NRAED is the number of time steps to read rainfall intensities (equal to integer ratio between rainfall recording time step and simulation time step). RRG data is read from the RAIN.DAT datafile.

11. General Variables : All of the following general variables are installed in DATA1 . The Lines of DATA1 include :

Line #1 :
    M = total number of rows
    N = total number of columns
    W = grid size (m)

NMAN = number of groups of overland Manning n
SDEP = overland detention storage (m)

Line #2 :
   DT = simulation time step (sec)
   NITER = total number of iterations
   NITRN = rainfall duration divided by DT
   NPRN = number of time steps between runoff discharge writings in output file
   NPLT = number of time steps to update graphics display

Line #3 :
   JOUT = outlet row number
   KOUT = outlet column number
   SOUT = uniform flow bed slope at outlet
   QMAX = maximum roughly predicted discharge to be used for graphics (cms)
   WCHOUT = channel width at outlet (m)
   DCHOUT = channel depth at outlet (m)
   RMANOUT = Manning channel roughness coefficient at outlet

Line #4 :
   INDEXINF = infiltration index; 1 for infiltration, 0 for no infiltration
   NSOIL = number of soils with different infiltration parameters

Line #5 :
   NCHN = total number of channels
   MAXCHN = maximum allowable number of channel elements plus one for any channel

Line #6 :
   IELPLT = elevation plotting index; 1 if topography is to be plotted, 0 if not
   ISOILLPLT = soil plotting index; 1 if soil map is to be plotted, 0 otherwise
   IDEPPLT = dynamic window plotting index; 1 for plotting, 0 otherwise

Line #7 :
   IRAIN = rainfall index; 1 for raingage data, 0 for uniform rainfall

Line #8 (when IRAIN = 1) :
   NRG = number of raingages
   NREAD = ratio between raingage rainfall data time step and DT

Line #8 (when IRAIN = 0) :
   CRN = uniform rainfall intensity (cm/hr)

The remaining portion of DATA1 contains raingage locations (XRG and YRG), if any, Manning n roughness coefficient values, and infiltration parameters.

For any graphics display, the graphics routine must be modified to accommodate a different watershed geometry (currently set up for Macks Creek of case study #4), and several other datafiles must be specified. ELCOL.DAT, RANCOL.DAT, DEPCOL.DAT, and INFCOL.DAT provide the range of the variable in the first column, and the color number corresponding to that range in the second column (files read in format I3,F15.0). There is another file, SOILCOL.DAT, whose only column has the color numbers corresponding to soil types (reading format in I3).

A complete example in the next section illustrates the procedure to prepare the necessary data for simulation.

5.2. Model Output

The model output file is named OUT.PRN. This output file contains the time (in min) in first column and the corresponding runoff discharge (in cms) in the second column. This file may easily be imported into graphics softwares for further analysis.

5.3. Before Using The Model

The computer model (printed in Appendix A) has been set up to simulate case study #4 in section 6.4. The model currently accommodates a 53×53 mesh. For larger watersheds, the dimension of both the predefined matrices including ISHP, E, IMAN, ISOIL, and the previously undefined matrices including H (for overland flow depth), HCH (for channel depth), RINT (for rainfall intensity), VINF (for infiltration depth), DQOV (for overland flow rate), and DQCH (for channel flow rate) must be changed within the program to the new dimension. If the number of raingages exceeds the current number in the program, which is 8, the dimension of the vectors XRG and YRG should be increased accordingly. For more than 10 groups of Manning n, the dimension of PMAN must be raised. Additionally, the dimension of ICHN and CHP are to be increased if NCHN and/or MAXCHN exceed the current values of 23 and 16, respectively.

For executing the graphics routine, the Microsoft Fortran Compiler version 5.0 is necessary. Also the directory for the graphic fonts in the very last part of the program (subroutine FONTS) must be checked and, if necessary, replaced.

For a given grid size, the time step should be selected small enough to ensure stability. Generally speaking, the more intense the rainfall, the steeper the watershed, and the smaller the grid size, the shorter the time step. For too long a time step, either negative depth results with the error message printed in the output file OUT.PRN or some oscillation is observed in the hydrograph. As such, the time step should be cut.

5.4. Simulation Example

The following example illustrates how to prepare input data for model simulations. The catchment used in this example is a part of Macks Creek Watershed for which most of the properties were modified solely for illustrative purposes. Therefore, the catchment characteristics do not necessarily have physical reality.

Fig . 3 shows the computer generated topographic map of the catchment along with its boundary and the grid mesh imposed on it. The square elements with an interior star (*) are located within the catchment. A 15×16 mesh covers the entire catchment (M = 15, N = 16), for a total of 240 elements. Only 135 elements are located within the catchment. The grid cell size is 200 m (W = 200). To prepare for the shape matrix, one can number rows and columns of the 15×16 mesh, as shown.
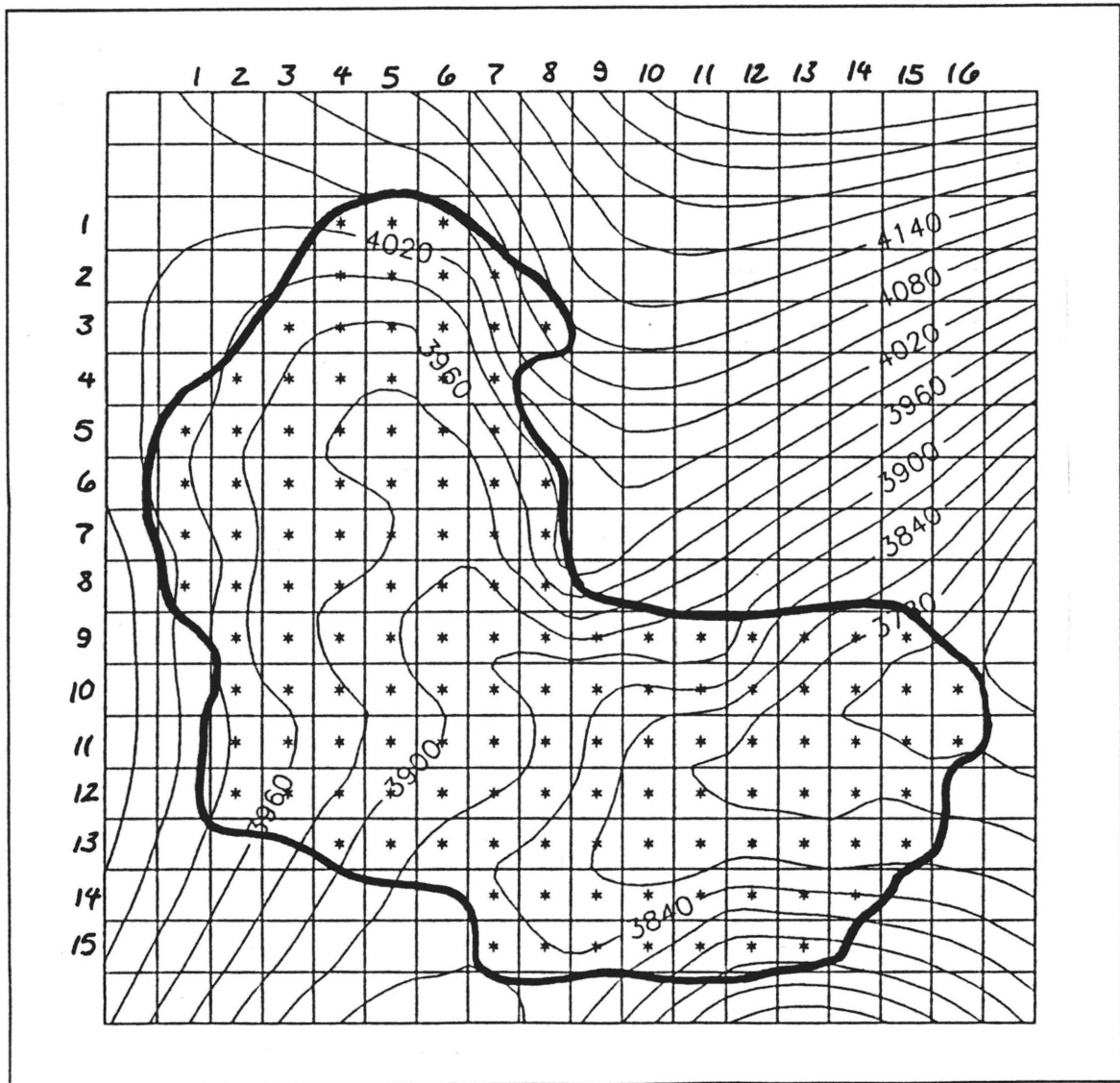
Figure 3. Catchment Geometry and Topographic Map

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Fig. 4 is a representation of channel delineation within the catchment. One main and two lateral channels are identified. However, the total number of channels with respect to the number of junctions, and the maximum channel length selected, would be at least 5 (A-E). We assume that channel C changes its characteristics along the channel, while other channels remain prismatic with respect to the channel width, depth, and roughness. This implies that at least 6 channels must be considered. The maximum length of channel is controlled by the longest channel which lies in the upper part of the catchment (channel number 1) and its length is equal to $8 \times W$. Therefore MAXCHN may be set to 9 or greater (Let MAXCHN be 9). The total number of channels is 6 (NCHN = 6) for the given value of MAXCHN. The data for each channel is reflected in file CHN.DAT. In Fig. 4, the numbers in parentheses are the channel numbers as used for the simulation.
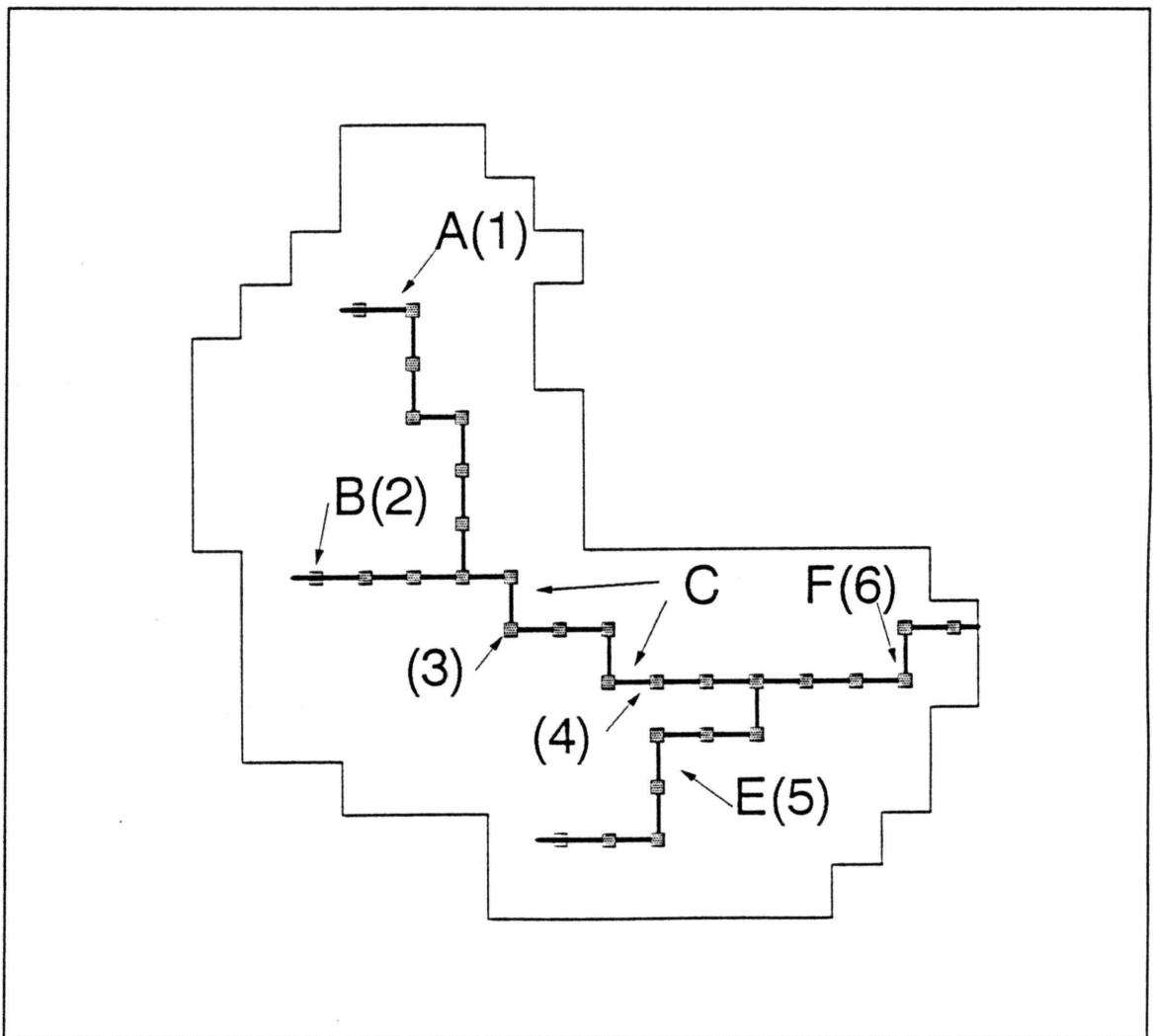
Figure 4. Channel Delineation in the Catchment

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The surface roughness was assumed to vary throughout the catchment. The number of Manning's roughness coefficient variations for this example is 4 (NMAN = 4) and these values were randomly distributed by the computer. Fig. 5 shows the computer generated random variation of n for each grid cell, in which group numbers (codes) 1 through 4 represent Manning coefficients of 0.04, 0.05, 0.06, and 0.07, respectively.
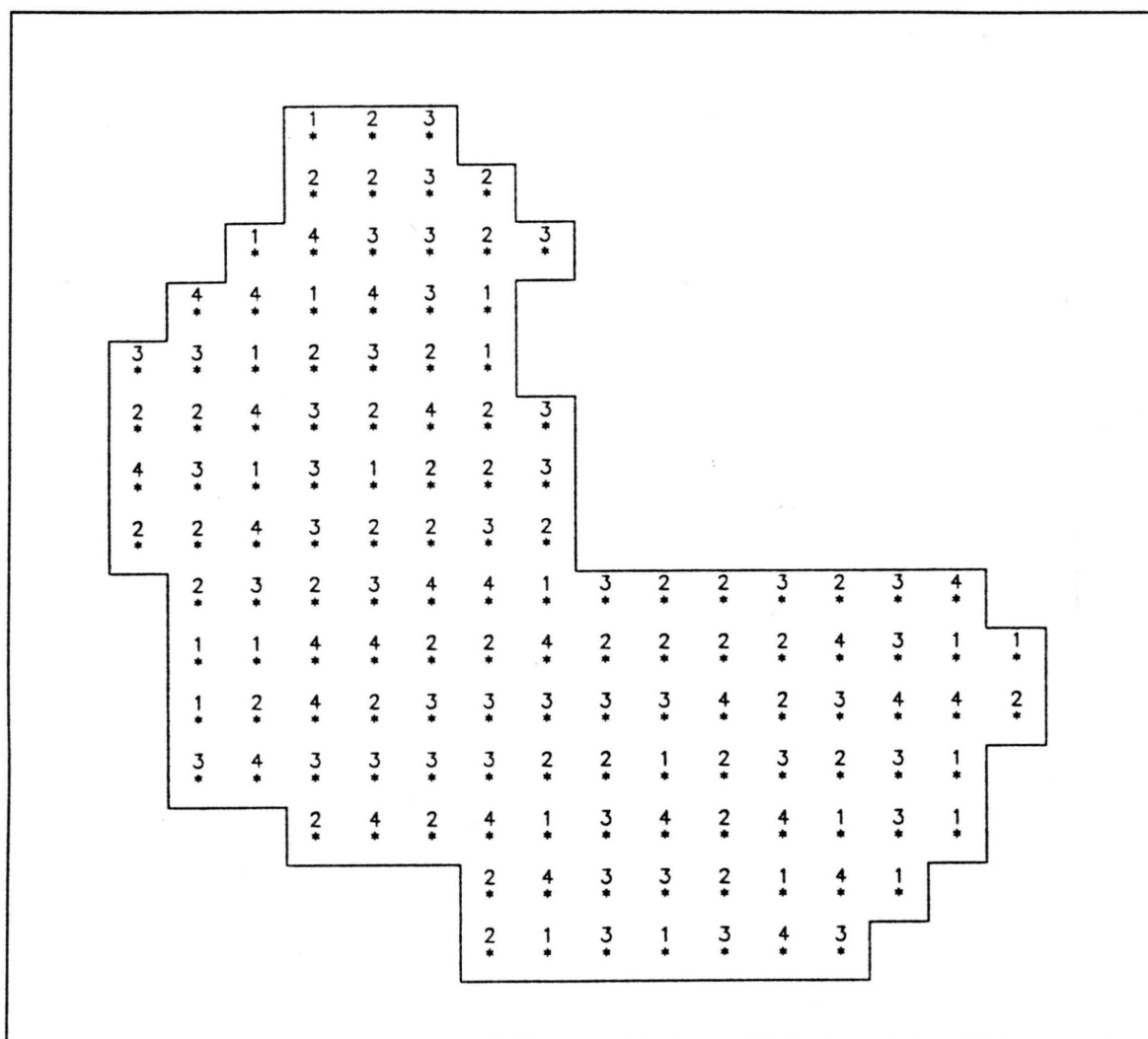
Figure 5. Roughness Coefficient Number Variations

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To determine the soil infiltration parameters, we assume that there are three different soil textures, each of which has two different initial soil moisture content values. This will require a total of 6 soil types with respect to the variations in soil infiltration parameters. Fig. 6 represents the soil number spatial variation at each element in the catchment. Soil group numbers 1 through 6 are assumed to have saturated hydraulic conductivities of 1E-6, 1E-6, 5E-7, 5E-7, 2E-7, and 2E-7 m/s, and capillary suction heads of 0.2, 0.2, 0.25, 0.25, 0.22, and 0.22 m, respectively. The initial soil moisture deficits are assumed to be 0.25, 0.1, 0.2, 0.15, 0.3, and 0.05, respectively. These data is recorded in DATA1 datafile.
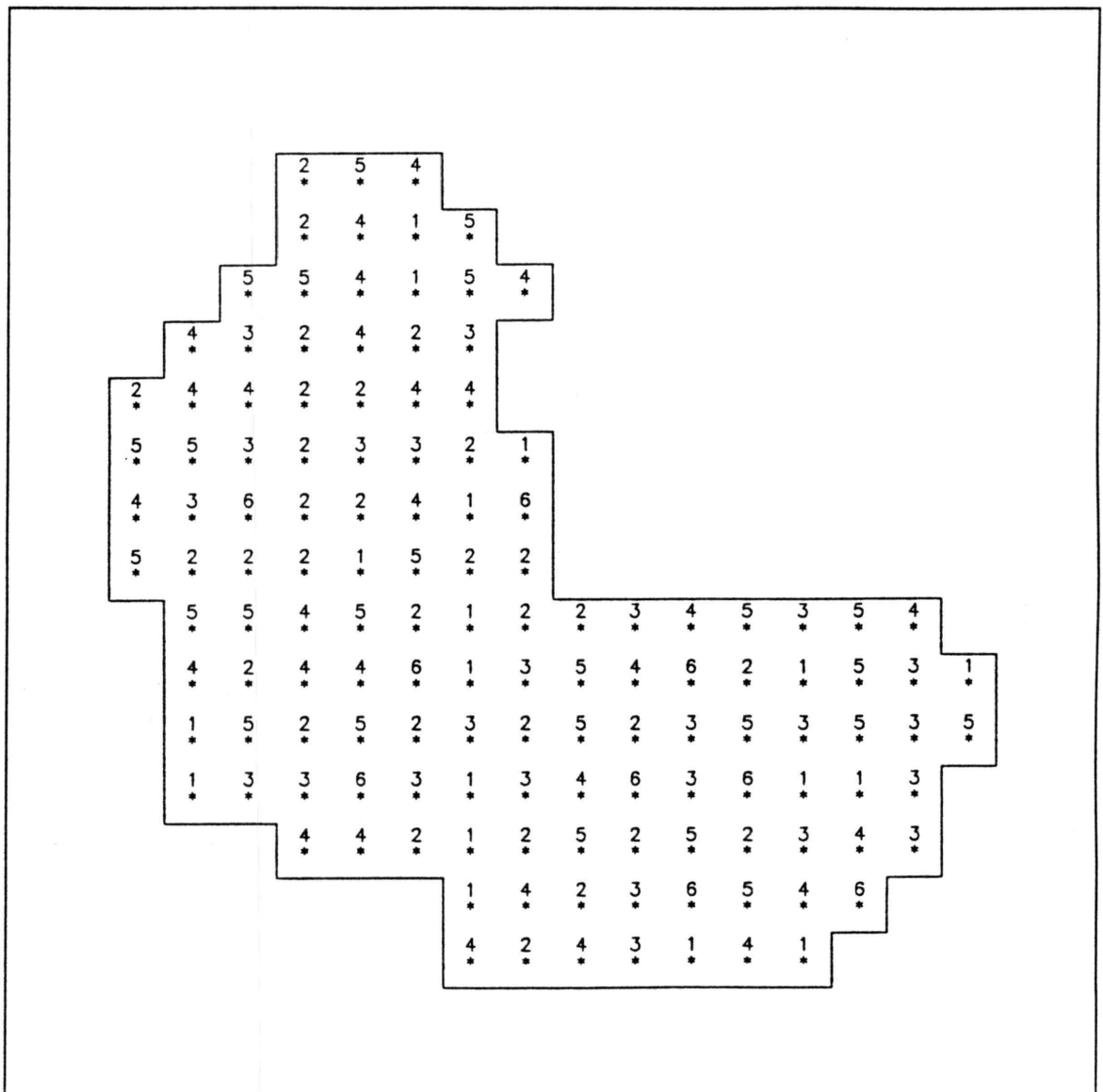
Figure 6. Soil Number at Each Element

The rainfall was assumed to be relatively dense and recorded by two raingages (NRG = 2), namely station A located at cell (5,5) and station B located at cell (12,13). The rainfall was recorded at 2 minute intervals. The rainfall time pattern, with a duration of 1 hour, will be shown in the RAIN.DAT file listing. The storm was simulated with 30-sec time steps for 2 hours (DT = 30, NITER = 240, NITRN = 120, NREAD = 4). The catchment outlet is located at cell (10,16) with an exit bed slope of 0.015 and outlet channel width, depth, and roughness of 4 m, 3 m, and 0.025, respectively (JOUT = 10, KOUT = 16, SOUT = 0.015, WCHOUT = 4., DCHOUT = 3., RMANOUT = 0.025). The results were recorded for each four time steps and plotted for each two time steps with an assumed maximum discharge of 30 cms (NPRN = 4, NPLT = 2, QMAX = 30.). The outflow hydrograph for this example is shown in Fig. 7.
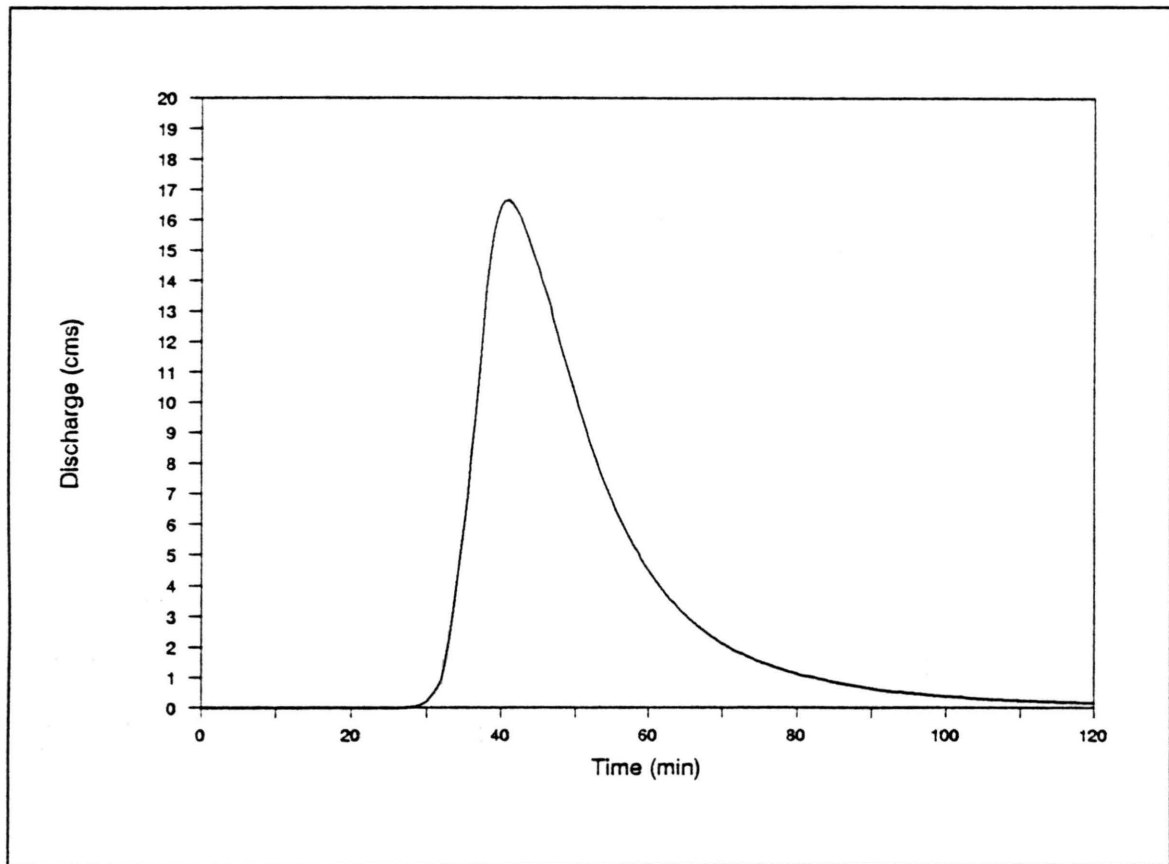
Figure 7. Outflow Hydrograph for Example Catchment

The datafiles and the output for this particular example follow. The program listing may also be found in Appendix A.

DATA1 FILE LISTINGS

NOTE : Format of this datafile is coded on p. 14 & 15. All variables with dimensions are in SI units. (reading format in *)

```
15      16      200.        4       0.
30.     240     120         4       2
10      16      0.015       30.     4.      3.      0.025
1       6
6       9
1       1       1
1
2       4
5       5      } raingages coordinates
12      13     }
0.04   ⎫
0.05   ⎬ Overland Manning n
0.06   ⎪
0.07   ⎭
1.0E-6      0.20    0.25   ⎫
1.0E-6      0.20    0.10   ⎪
5.0E-7      0.25    0.2    ⎬ Soil Infiltration Parameters
5.0E-7      0.25    0.15   ⎪
2.0E-7      0.22    0.3    ⎪
2.0E-7      0.22    0.05   ⎭
```

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MODIFIED SHAP.DAT FILE LISTING

NOTE : To make the SHAP.DAT file, the following columns (starting with the first column) must be inserted into a single column. (reading format in *)

```
      0    0    1    0    0
      0    1    1    1    0
      0    1    1    1    0
      1    1    1    1    1
      1    1    1    1    1
A →   1    1    1    1    1
      0    1    1    1    1
      0    0    1    1    1
      0    0    0    1    1
      0    0    0    1    1
      0    0    0    1    1
      0    0    0    1    1
      0    0    0    1    1
      0    0    0    1    1
      0    0    0    1    1
      0    0    0    1    0
      0    1    1    0    0
      0    1    1    1    0
      0    1    1    1    0
      1    1    1    1    0
B →   1    1    1    1    0
      1    1    1    1    0
      1    1    1    1    1
      0    0    1    1    1
      0    0    0    1    1
      0    0    0    1    1
      0    0    0    1    1
      0    0    0    1    1
      0    0    0    1    1
      0    0    0    1    1
      0    0    0    1    0
      0    0    0    1    0
      0    1    0    0    0
      0    1    1    1    0
      1    1    1    1    0
      1    1    1    1    0
      1    1    1    1    0
      1    1    1    1    0
      1    1    1    1    1
      1    1    1    1    1
      0    0    1    1    1
      0    0    1    1    1
      0    0    1    1    1
      0    0    1    1    1
      0    0    1    1    1
      0    0    1    1    0
      0    0    1    1    0
      0    0    0    0    0
```

MODIFIED ELAVG.DAT FILE LISTING

NOTE : To make the ELAVG.DAT file, the following columns (starting with the first column) must be inserted into a single column. Unit is in meters and reading format in * .

A ← 4040	3920	3970	3825
4020	3980	3950	3820
4040	4040	3920	3810
B ← 3990	3960	3910	3800
4000	3950	3895	3835
3990	3940	3885	3840
4060	3930	3807	3830
C ← 3965	3885	3792	3830
3960	3900	3776	3860
3955	4020	3760	3830
3950	3955	3752	3840
4035	3940	3744	3855
4100	3920	3736	3920
D ← 3980	3895	3740	3910
3955	3880	3980	3920
3935	3867	3960	
3925	3915	3930	
3945	3895	3900	
4020	3870	3890	
4010	3880	3880	
3970	3840	3860	
3950	3805	3830	
3930	3785	3784	
3920	3780	3776	
3925	3970	3768	
3970	3950	3780	
3985	3930	3800	
3955	3910	3760	
3940	3890	3900	
3920	3852	3875	
3915	3837	3860	
3900	3822	3855	
3940	3860	3840	
3980	3890	3810	
4000	3810	3792	
3970	3775	3795	
3960	3750	3805	
3960	3728	3785	
3940	3720	3800	
3890	3990	3805	

A ← 4040 4020 4040
B ← 3990 4000 3990 4060
C ← 3965 3980 3955 3950 4035 4100
D ← 3980 3955 3935 3925 3945 4020
4010 3970 3950 3930 3920 3925 3970
3985 3955 3940 3920 3915 3900 3940 3980
4000 3970 3960 3960 3940 3890 3920 3980
4040 3960 3950 3940 3930 3885 3900 4020
3955 3940 3920 3895 3880 3867 3915 3895 3870 3880 3840 3805 3785 3780
3970 3950 3930 3910 3890 3852 3837 3822 3860 3890 3810 3775 3750 3728 3720
3990 3970 3950 3920 3910 3895 3885 3807 3792 3776 3760 3752 3744 3736 3740
3980 3960 3930 3900 3890 3880 3860 3830 3784 3776 3768 3780 3800 3760
3900 3875 3860 3855 3840 3810 3792 3795 3805 3785 3800 3805
3825 3820 3810 3800 3835 3840 3830 3830
3860 3830 3840 3855 3920 3910 3920

MODIFIED IMAN.DAT FILE LISTING

NOTE : To make the IMAN.DAT file, the following columns (starting with the first column) must be inserted into a single column. (reading format in *)

Col 1	Col 2	Col 3
1 (A)	2	2
2 (A)	3	4
3 (A)	2	3
2 (B)	2	3
2 (B)	4	2
3 (B)	3	1
2 (B)	2	4
1 (C)	2	1
4 (C)	3	2
3 (C)	2	1
3 (C)	2	3
2 (C)	3	1
3 (C)	2	3
4 (D)	3	4
4 (D)	4	3
1 (D)	4	
4 (D)	1	
3 (D)	3	
1 (D)	2	
3	2	
3	3	
1	2	
2	3	
3	4	
2	1	
1	1	
2	4	
2	4	
4	2	
3	2	
2	4	
4	2	
2	2	
3	2	
4	2	
3	4	
1	3	
3	1	
1	1	
2	1	

A→ 1 2 3
B→ 2 2 3 2
C→ 1 4 3 3 2 3
D→ 4 4 1 4 3 1
3 3 1 2 3 2 1
2 2 4 3 2 4 2 3
4 3 1 3 1 2 2 3
2 2 4 3 2 2 3 2
2 3 2 3 4 4 1 3 2 2 3 2 3 4
1 1 4 4 2 2 4 2 2 2 2 4 3 1
1 2 4 2 3 3 3 3 3 4 2 3 4 4 2
3 4 3 3 3 3 2 2 1 2 3 2 3 1
2 4 2 4 1 3 4 2 4 1 3 1
2 4 3 3 2 1 4 1
2 1 3 1 3 4 3

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MODIFIED SOIL.DAT FILE LISTING

NOTE : To make the SOIL.DAT file, the following columns (starting with the first column) must be inserted into a single column. (reading format in *)

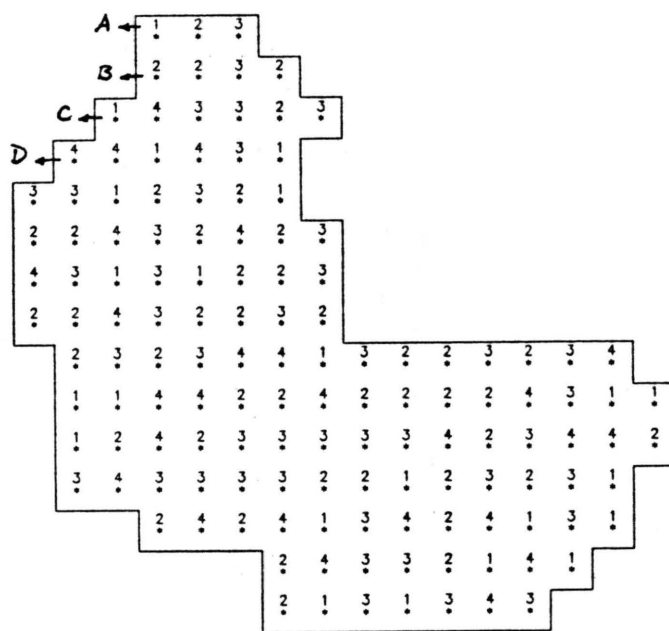| Col 1	Col 2	Col 3	Col 4
A 2	1	5	1
A 5	6	2	4
A 4	5	5	2
B 2	2	2	3
B 4	2	3	6
B 1	2	2	5
B 5	1	5	4
C 5	5	2	6
C 5	2	3	4
C 4	2	5	2
C 1	5	3	4
C 5	5	5	3
C 4	4	3	1
D 4	5	5	4
D 3	2	1	1
D 2	1	3	
D 4	2	3	
D 2	2	6	
D 3	3	3	
2	4	1	
4	5	3	
4	3	4	
2	5	6	
2	4	3	
4	4	6	
4	2	1	
5	4	1	
5	4	3	
3	6	4	
2	1	4	
3	3	2	
3	5	1	
2	4	2	
1	6	5	
4	2	2	
3	1	5	
6	5	2	
2	3	3	
2	1	4	
4	1	3	

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CHN.DAT FILE LISTING

NOTE : Units of channel widths and depths (two first columns of first six lines) in meters, reading format in * for the first six lines, and /9I3/9I3 for the rest.

	Width	Depth	Manning n
(1) ←	2.0	2.0	0.04
(2) ←	1.5	1.5	0.04
(3) ←	2.5	2.0	0.035
	3.0	2.5	0.03
	2.0	2.0	0.04
	4.0	3.0	0.025


```
        a    b    c    d    e    f    g    h
(1) ←   4    4    5    6    6    7    8    9   -1*
        4    5    5    5    6    6    6    6   -1

        i    j    k    h
(2) ←   9    9    9    9   -1    0    0    0    0**
        3    4    5    6   -1    0    0    0    0

        h    l    m    n
(3) ←   9    9   10   10   -1    0    0    0    0
        6    7    7    8   -1    0    0    0    0

       10   10   11   11   11   11   -1    0    0
        8    9    9   10   11   12   -1    0    0

       14   14   14   13   12   12   12   11   -1
        8    9   10   10   10   11   12   12   -1

       11   11   11   11   10   10    0    0    0
       12   13   14   15   15   16    0    0    0
```
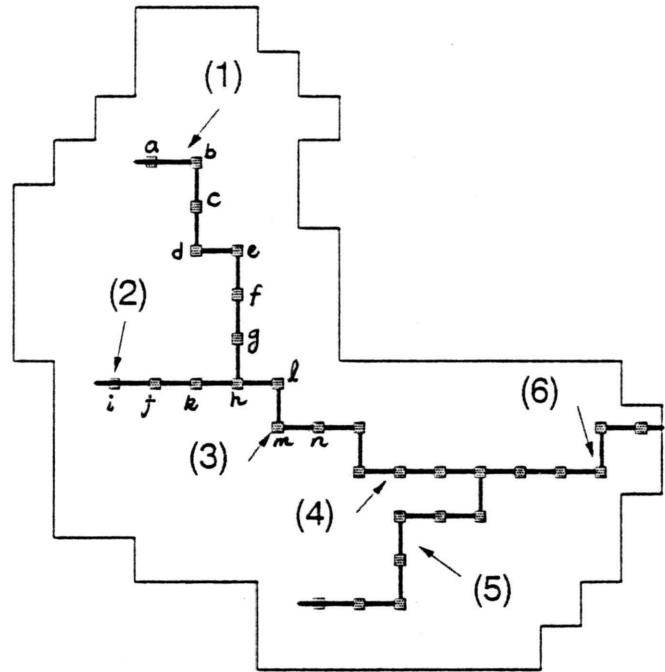
* : Negative numbers indicate channel junction at preceding location.

** : As a channel ends, the remaining space up to MAXCHN is filled with zeros.

RAIN.DAT FILE LISTING

NOTE : Rainfall Intensities in cm/h recorded every 2 minutes, reading format in F9.3.

Station A	Station B
0.500	0.000
1.000	0.500
1.000	0.500
1.000	1.000
1.000	1.000
1.500	1.000
1.500	1.000
1.500	1.500
1.500	2.000
1.500	2.500
1.500	2.500
4.800	2.500
4.800	2.500
4.800	2.500
4.800	2.500
4.060	4.800
0.740	15.600
0.740	9.600
0.740	3.680
0.740	1.320
0.740	1.320
0.740	1.320
0.044	1.320
0.044	0.054
0.044	0.054
0.044	0.054
0.044	0.054
0.044	0.054
0.044	0.054
0.044	0.054

ELCOL.DAT FILE LISTING

Note : Color codes in first column, elevation ranges (m) in second column, reading format in I3,F15.0. (Example : elevation greater than 1000 m and less than 1100 m has a color code of 7.)

```
14    1000.
 7    1100.
11    1120.
 3    1140.
 9    1160.
 1    1180.
13    1200.
 5    1220.
12    1240.
 6    1260.
```

SOILCOL.DAT FILE LISTING

NOTE : Color codes for each soil type, format in *

```
 7
11
 3
 9
 5
12
```

RANCOL.DAT FILE LISTING

Note : Color codes in first column, rainfall intensity ranges (cm/hr) in second column, reading format in I3,F15.0. (Example : rainfall intensity greater than 0.01 cm/hr and less than 0.1 cm/hr has a color code of 7.)

```
 8    0.01
 7    0.1
11    0.25
 3    0.5
 9    1.
 1    2.5
13    5.
14    10.
12    15.
 6    20.
```

DEPCOL.DAT and INFCOL.DAT FILE LISTING

Note : Color codes in first column, depth ranges (m) in second column, reading format in I3,F15.0. (Example : depth greater than 2 m and less than 5 m has a color code of 5.)

```
  8         0.000001
  7         0.00001
 11         0.0001
  3         0.001
  9         0.01
  1         0.1
 14         1.
 13         2.
  5         5.
  4        10.
```

OUT.PRN FILE LISTING

Time (min)	Discharge (cms)
0.00	0.00000
2.00	0.00000
4.00	0.00000
6.00	0.00000
8.00	0.00000
10.00	0.00000
12.00	0.00000
14.00	0.00000
16.00	0.00000
18.00	0.00000
20.00	0.00000
22.00	0.00000
24.00	0.00009
26.00	0.00380
28.00	0.04109
30.00	0.21929
32.00	0.92613
34.00	4.26555
36.00	8.34563
38.00	13.76445
40.00	16.49489
42.00	16.36333
44.00	15.13286
46.00	13.63847
48.00	11.88864
50.00	10.22593
52.00	8.69017
54.00	7.35394
56.00	6.23130
58.00	5.29187
60.00	4.50522
62.00	3.84319
64.00	3.29334
66.00	2.83515
68.00	2.45061
70.00	2.12820
72.00	1.85629
74.00	1.62658
76.00	1.43689
78.00	1.27567
80.00	1.13574
82.00	1.01306
84.00	0.90480
86.00	0.80878
88.00	0.72336
90.00	0.64740
92.00	0.58059
94.00	0.52252
96.00	0.47211
98.00	0.42810

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Time (min)	Discharge (cms)
100.00	0.38936
102.00	0.35500
104.00	0.32440
106.00	0.29707
108.00	0.27267
110.00	0.25088
112.00	0.23142
114.00	0.21402
116.00	0.19842
118.00	0.18439
120.00	0.17174

6. MODEL EVALUATION

Several cases of model performance have been compared with either analytical or experimental results. These case studies include : one dimensional kinematic wave, converging plane, Johns Hopkins Parking Lot #1, and Macks Creek watershed.

6.1. Case Study #1 : 1-D Kinematic Wave

The model, though originally a diffusive wave model, was slightly modified to formulate the kinematic wave for which solution by the characteristics method is known for the one-dimensional case (Woolhiser, 1975). A single plane, 100-m long, sloping 9% was assumed with uniform precipitation equal to 2.4×10^{-6} m/s. The width of the plane is controlled by grid size (W). The model was further modified to accommodate for the laminar flow regime, assuming $K = 208.3$, with kinematic viscosity of 1×10^{-6} m/s. The kinematic time to equilibrium for the given conditions may be calculated as :

$$T_e = (\frac{K \nu L}{8 g S_0 i^2})^{1/3} = 800 \, sec$$

where L = length of the plane

Three rainfall durations (T_r), 600, 800, and 1200 sec were tested to represent partial, $T_r = T_e$, and complete equilibrium conditions, respectively. The results of model simulations are compared with the analytical solution in Fig. 8. For all cases, $W = 2.5$ m, $DT = 10$ sec.

The agreement supports the accuracy of the model formulation in one dimension. The numerical solution partially demonstrates a dynamic effect as the computed hydrograph approaches its peak. This smoothing effect is desirable. A larger grid size tends to highlight the aforementioned effect, which causes a magnified difference between peak values for $T_r = T_e$ equilibrium case. This is expected for current model formulation which coincides with first order finite difference formulation for these given conditions. A minimum number of 20 elements is recommended for any case.

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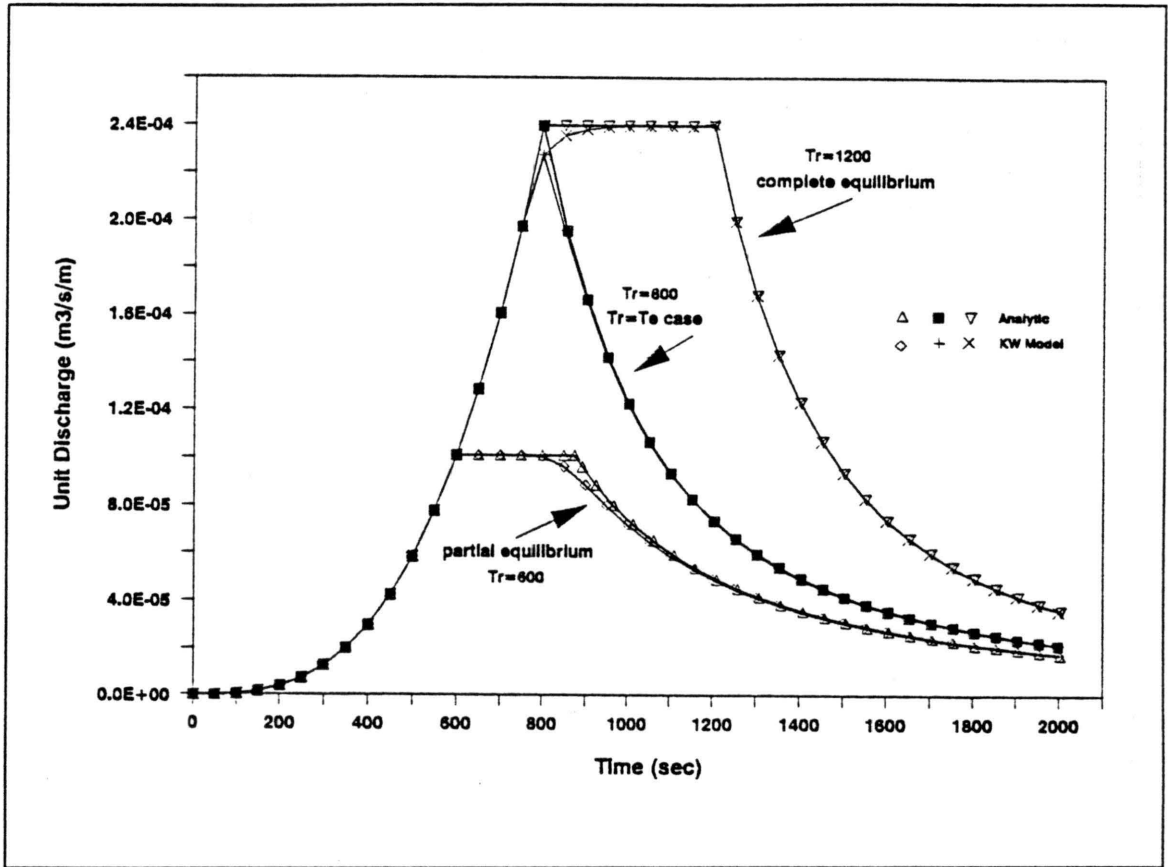
Figure 8. Hydrographs from Case Study #1

6.2. Case Study #2 : Converging Plane

The converging plane consists of a V-shaped section plus a portion of the surface of a cone (Fig. 9). The continuity equation describing the converging overland flow, a special type of radial flow, has been derived by Veal (1966) :

$$\frac{\partial h}{\partial t} + u_r \frac{\partial h}{\partial x_r} + h \frac{\partial u_r}{\partial x_r} = e + \frac{u_r h}{L_0 - x_r}$$

where x_r = the radial direction
u_r = average local velocity in radial direction

and other variables as defined before.
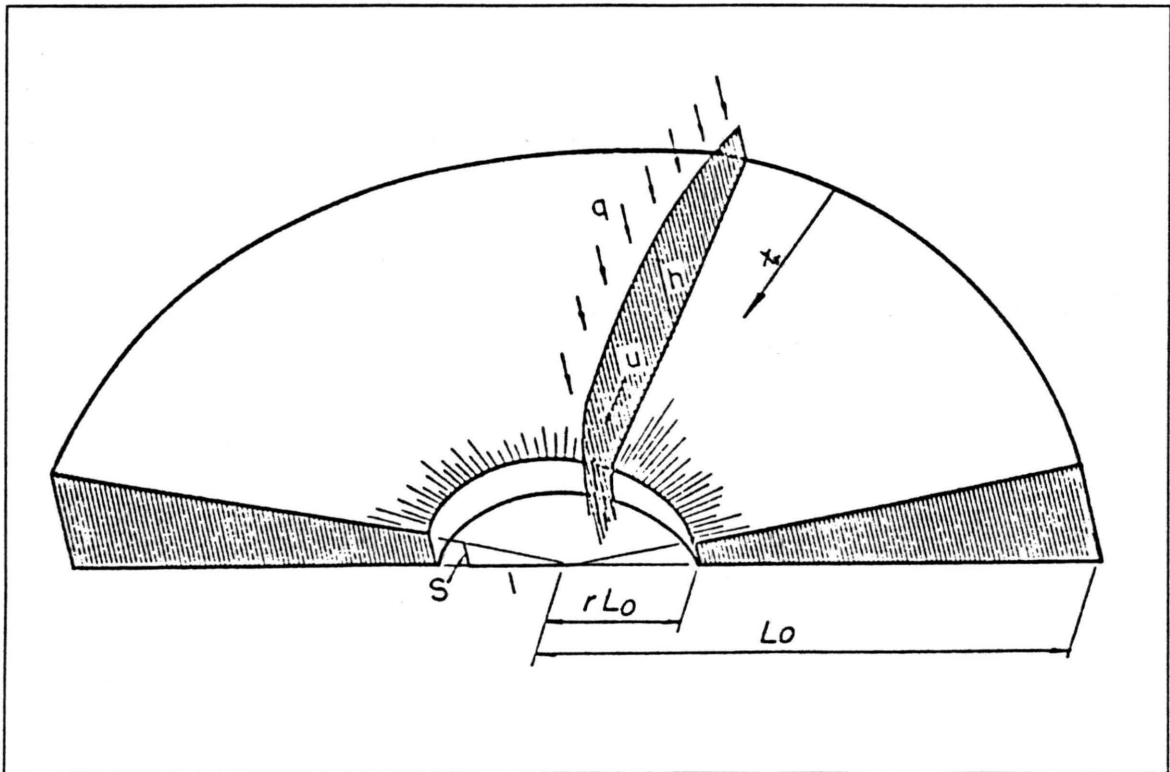
Figure 9. Converging Plane

Woolhiser (1969) solved the nonlinear, nonhomogeneous, ordinary differential equations of characteristic ground curves, deduced from non-dimensionalized equations of continuity and kinematic wave equation, by the finite difference technique. This solution, plus the experimental observed data from a converging plane, became another basis for model verification. Clearly this case is considered a two-dimensional overland flow in conventional Cartesian coordinate system, as used in the current model. A 30° slice of the converging section, $L_0 = 100$ ft, $r = 0.1$, $S_0 = 0.05$, was digitized into 104 square elements with $W = 5$ ft (A smaller grid size may better represent the

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outlet, if more accuracy is sought). Rainfall intensity of i = 1 iph was hypothetically imposed upon the plane with two different durations, 62.5 sec and 90 sec. The former intensity generates a partial equilibrium condition and the latter, a complete equilibrium condition. The model was adjusted to accommodate the Chezy resistance formula, with Chezy C equal to 100 ft$^{1/2}$/sec. A time step of 2.5 sec was found adequate to avoid instability. The downstream boundary condition is such that critical depth prevails if flow is subcritical and normal depth occurs if flow is supercritical. The runoff hydrographs, as simulated, along with Woolhiser's solution are presented in Fig. 10.
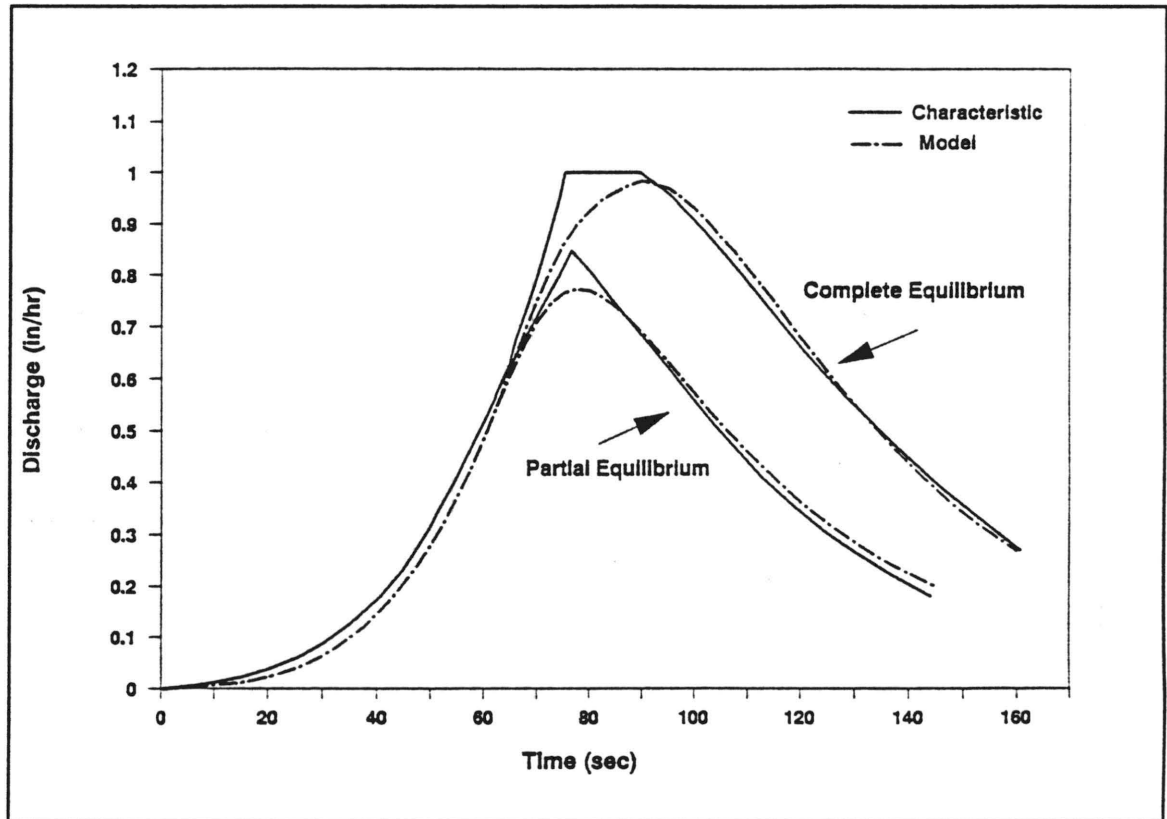
Figure 10. Hydrographs from Case Study #2 : Hypothetical

Experimental data have also been obtained for converging overland flow at Colorado State University, as reported by Dickinson, Holland, and Smith (1967). Runoff from a 120° sector with $L_0 = 110$ ft, and r = 0.016 covered with butyl rubber, was studied while under spatially uniform rainfall intensities of 1.04 iph and 2.39 iph, with durations of 80 sec and 75 sec, respectively. For model simulation, a square mesh of size 4.56 ft (1.39 m) was overlaid on half of the symmetric plane (60° sector), which resulted in 297 elements. A 2-sec time step properly simulated the runoff with no numerical instability. Manning n was estimated at 0.015. Once again the observed and computed hydrographs are shown together on Figs. 11 and 12.
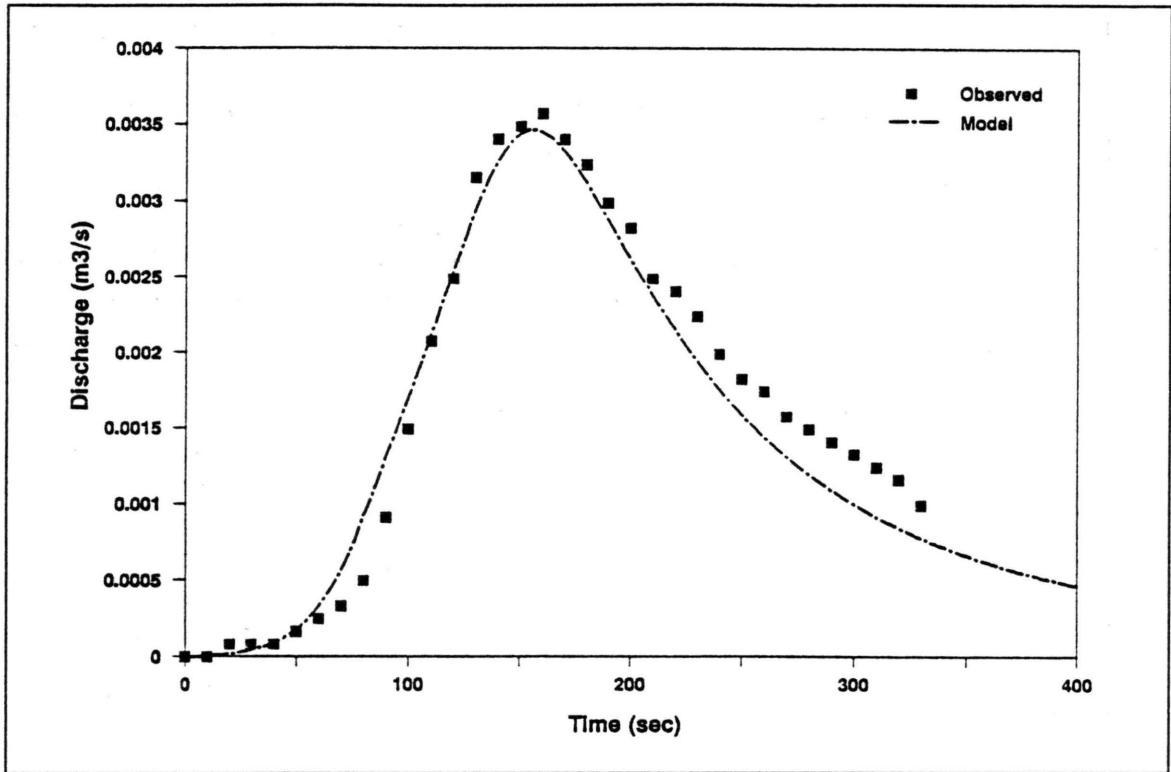
Figure 11. Hydrographs from Case Study #2. Experimental 1
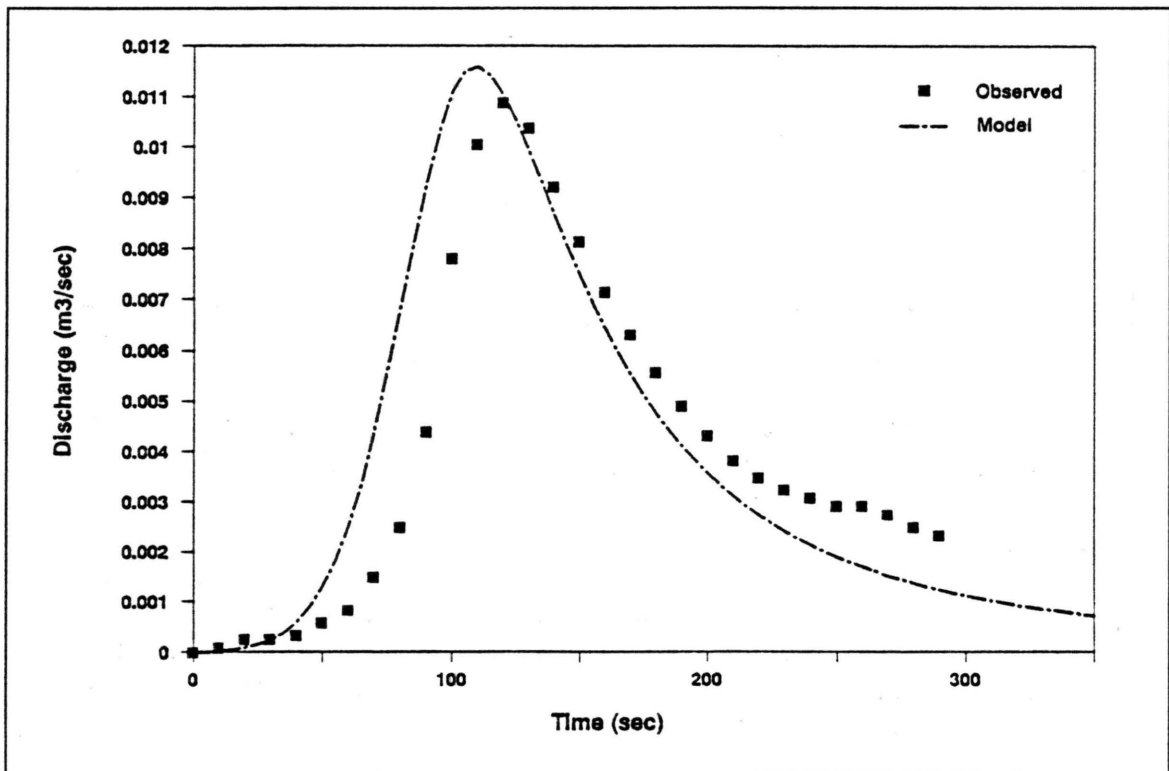
Figure 12. Hydrographs from Case Study #2 : Experimental 2

6.3. Case Study #3 : Johns Hopkins University Parking Lot

Johns Hopkins University South Parking Lot #1, SPL1, is an example of a paved surface over which overland flow may be generated without any losses due to infiltration. The geometry description of SLP1 is shown in Fig. 13. The lot has an area of 0.395 acres, covered by asphalt. The surface runoff is measured with a weir located at the storm water inlet. Rainfall records were obtained from a tipping bucket raingage located adjacent to the lot. The rainfall-runoff data for the current study were taken from Schaake's (1965) dissertation. Among several storms reported, only the most mass conservative ones were selected; namely storm numbers 3, 7, 13, and 18. The rainfall volumes recorded for those storms were 0.54, 0.33, 1.11, and 0.28 inches, and the volumes of runoff were 0.49, 0.33, 0.93, and 0.25 inches, respectively. Based on the volume of runoff, the percentage of error in recording the rainfall were estimated as 10, 0, 19, and 12. The difference between rainfall and runoff volumes can be mainly attributed to spatial variations of the rainfall, which can't be captured by a single raingage. Therefore, storm #7 was selected as the primary event for model verification and the others were analyzed qualitatively.

A square size of W = 20 ft (6.1 m) divided the parking lot into 43 total elements (M = 16, N = 5). The elevation at the center of each element was read from the topographic map and inserted in ELAVG.DAT datafile. Laminar flow was assumed to dominate at the very beginning of the runoff, with K being 80. At a Reynolds number of 500, the flow becomes turbulent with Manning n = 0.014 for asphalt. It should be emphasized that the laminar flow portion didn't significantly affect the hydrograph and the turbulent flow region controlled the whole runoff. A 5-sec time step was used for simulation. For downstream normal depth calculations, the average slope near the outlet was taken as 0.02, as measured from topographic map.

A nearly perfect simulation was obtained for storm #7. The results (Figs. 14-17) are also very encouraging for other storms, in which the computed hydrograph has been slightly overestimated due to excess rainfall.

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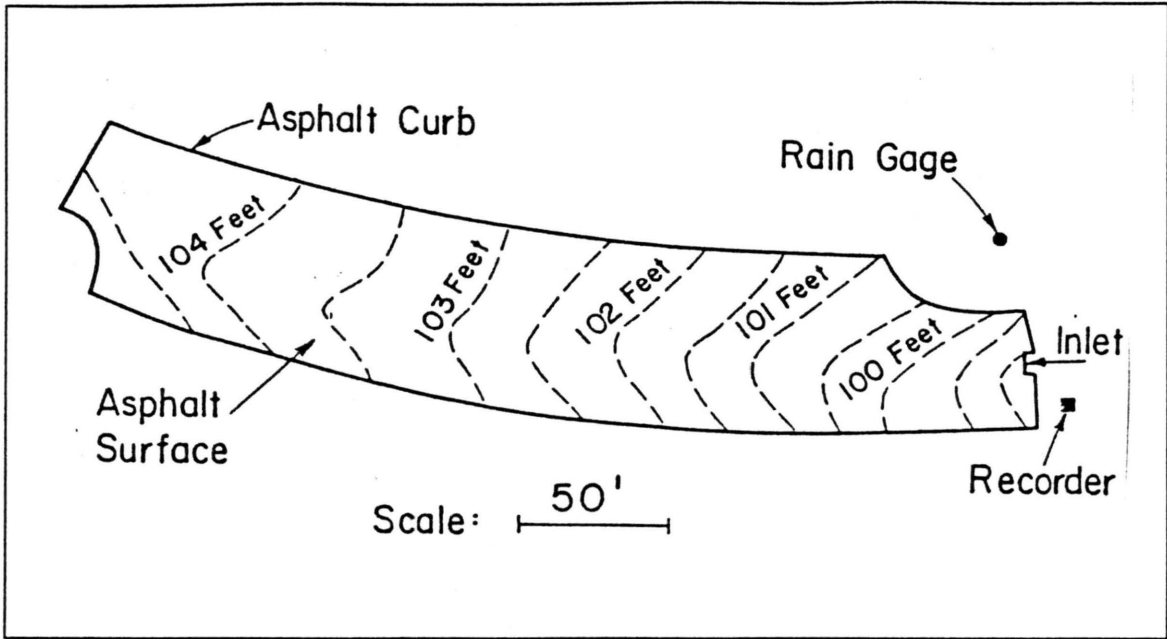
Figure 13. Johns Hopkins University Parking Lot
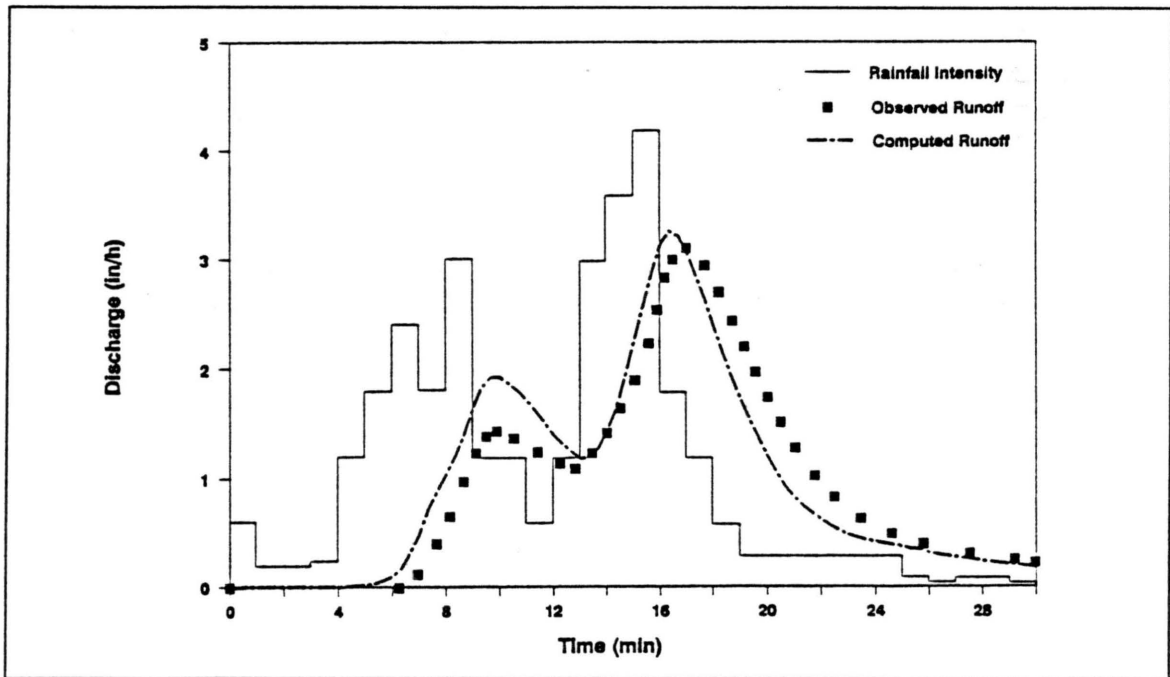
Figure 14. Hydrographs from Case Study #3 : Storm #3
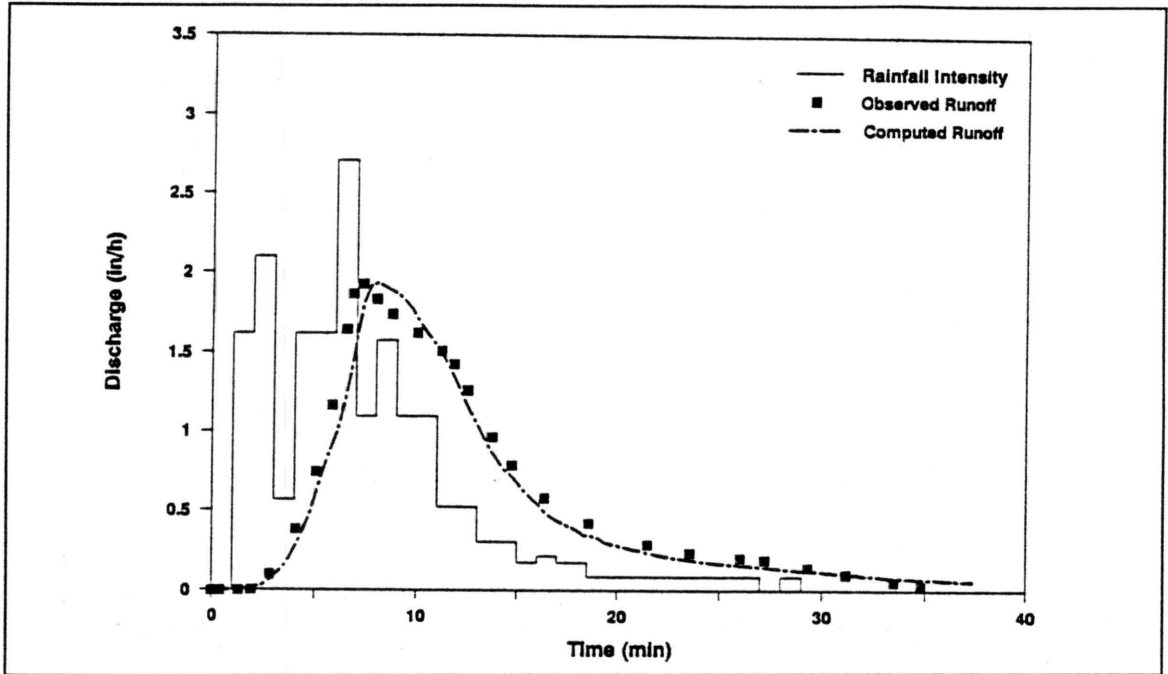
Figure 15. Hydrographs from Case Study #3 : Storm #7
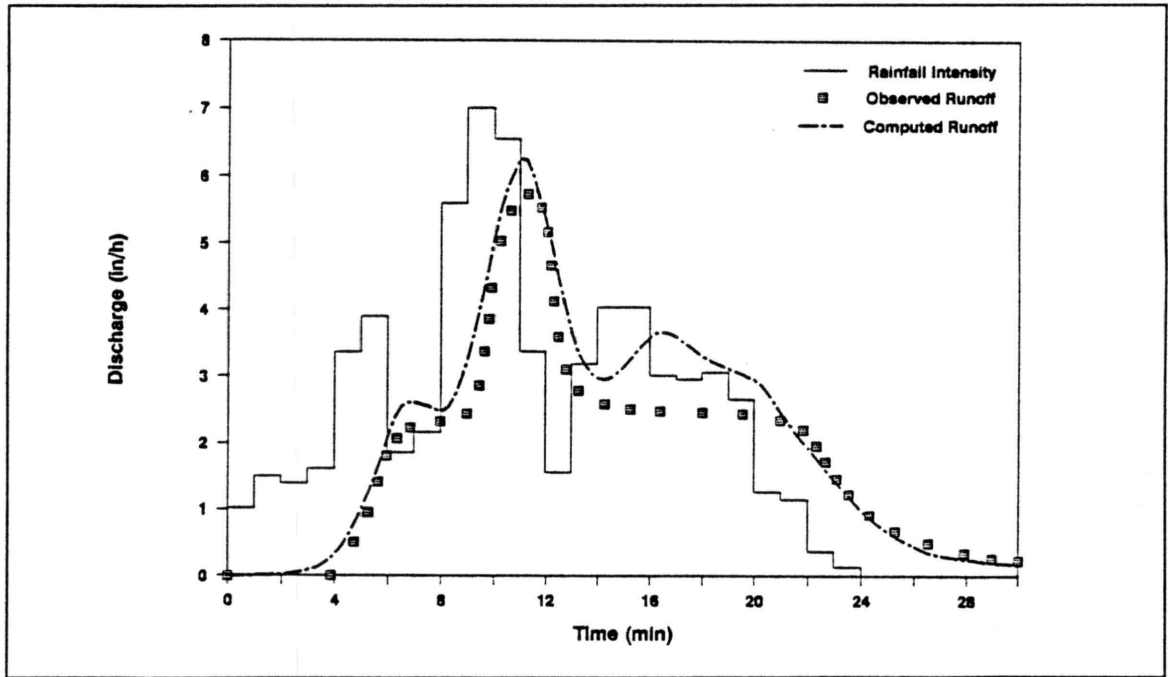
Figure 16. Hydrographs from Case Study #3 : Storm #13

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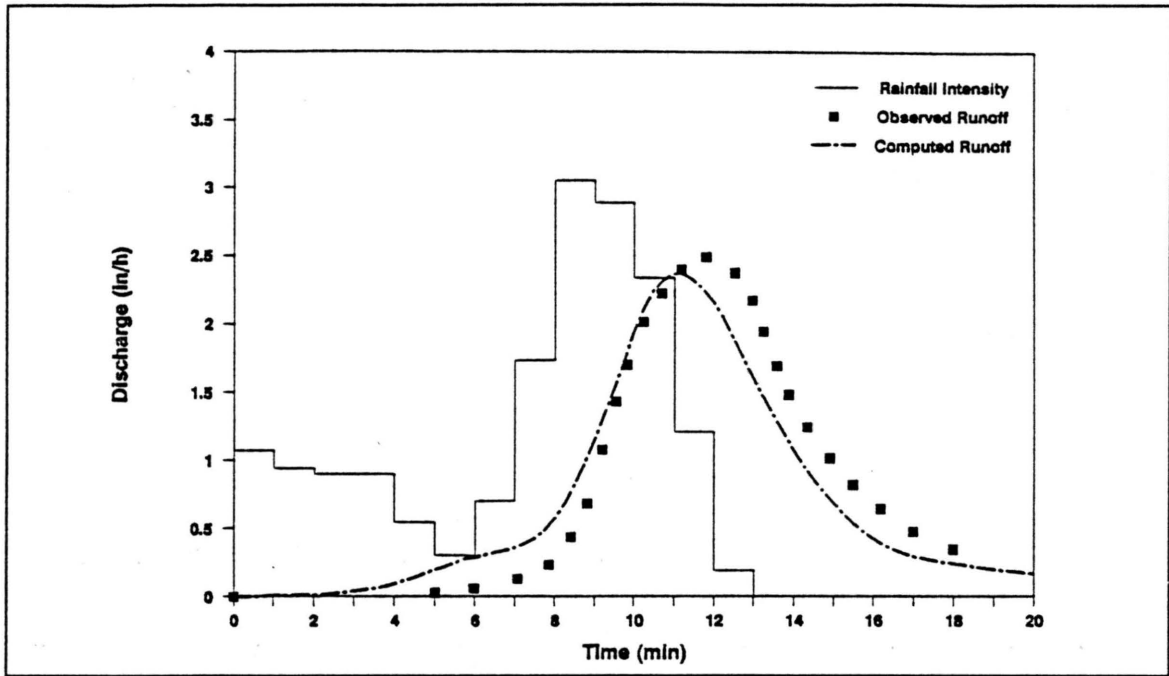
Figure 17. Hydrographs from Case Study #3 : Storm #18

6.4. Case Study #4 : Macks Creek Watershed

Macks Creek, one of the subbasins of the Reynolds Creek Experimental Watershed, is a small arid mountainous watershed located in southwest Idaho. Macks Creek drains approximately 12.3 square miles in the north and west portion of Reynolds Creek Watershed. Elevations range from about 6000 ft in the mountainous areas in the west to about 3700 ft near the outlet. Fig. 18 shows a topographic map of Macks Creek with contours at 40 feet intervals. Overland flow slope ranges from 7% to 30%. Channel slopes can range up to 8% but average about 5%. Two principal channels, each almost 6 miles long, collect surface runoff. One channel flows easterly from the northern section of the watershed, and the other flows northeasterly from southern section. Precipitation, baseflow, and a few springs are the main sources of water. A relatively dense raingage network, at approximately one per square mile, records the precipitation intensity. The runoff is measured with a precalibrated 3500 cfs capacity drop box weir. In 1966, for example, mean monthly runoff varied from 2.1 cfs in March to 0.02 cfs in September. Mean daily discharges ranged from 7.8 cfs on March 13 to 0.01 cfs in October of the same year. Fig. 19 illustrates channel delineation in the watershed along with the location of the raingages and the weir.

For simulating the Macks Creek Watershed, a rainfall event which occurred on August 23, 1965 was selected. Rainfall data was available from 8 raingages located on or near the watershed (Fig. 20), along with corresponding runoff data for the weir at the outlet of Macks Creek Watershed. The quantity of accumulated rainfall volume varied from 0.63 inches at gage 045/04 to 0.09 inches at gage 072/67. Gage 055/88 measured no rainfall for this event. Base flow varied between 0.4 cfs and 0.8 cfs at the weir, but it was neglected in the simulation when compared to peak discharge. Observed peak runoff for this storm was 85.14 cfs at 65 minutes after the beginning of the storm. However, the actual peak might have occurred between 65 and 75 minutes.

A square grid size of 496 ft (151.2 m) was assigned, which resulted in a shape matrix (ISHP) of 53×53 (M = 53, N = 53). By overlying the grid mesh, the total number of elements within the watershed was determined to be 1390, the remainder (1419) being outside the boundaries of the watershed. The elevation of the center of each grid cell was determined and put in ELAVG.DAT. Rainfall data was arranged in RAIN.DAT for 8 raingages.

Figure 18. Macks Creek Topographic Map
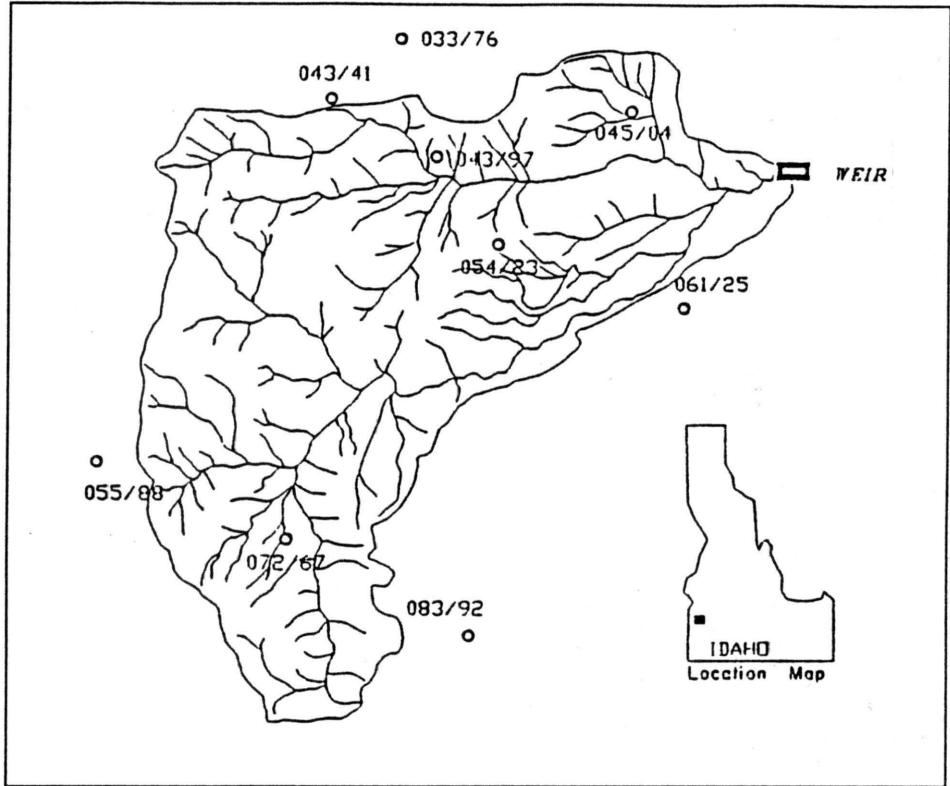
Figure 19. Channel Delineation and Raingages Locations
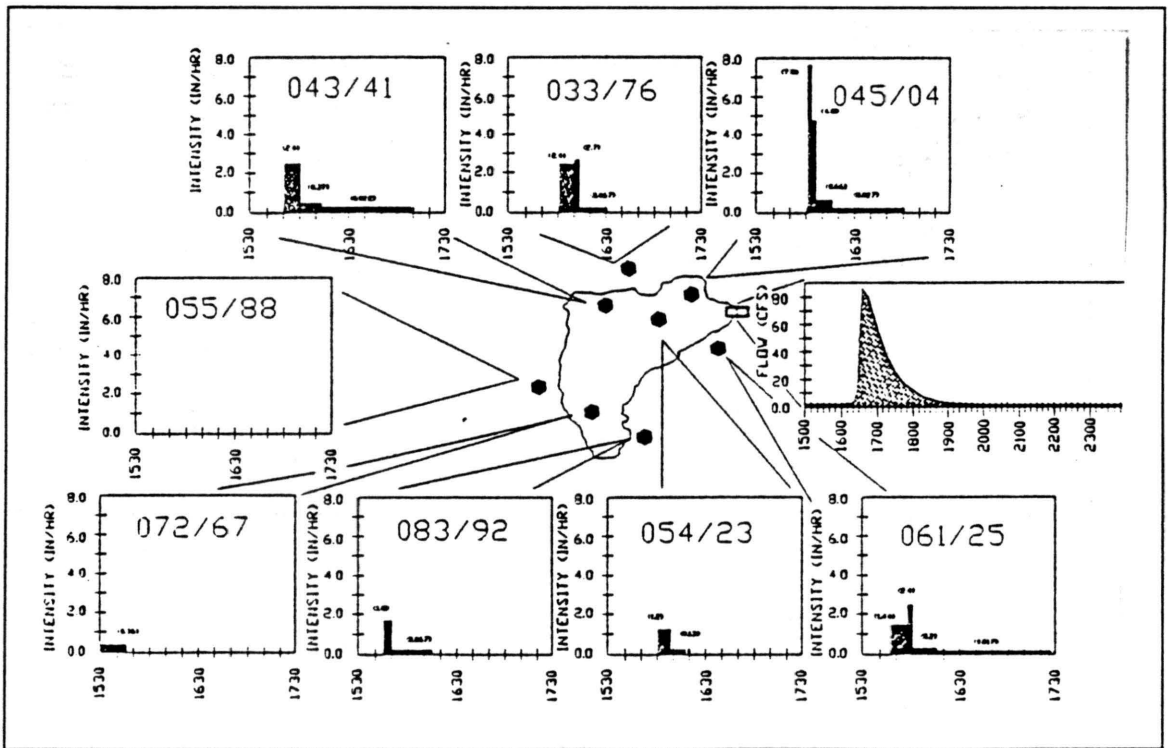
Figure 20. Measured Hyetograph and Outflow Hydrograph

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To account for infiltration losses, infiltration data must be prepared. This is done by first grouping the major soil types. Soil types in the area are dominantly gravelly, rocky, and stony loams with soil depths ranging from 7 to 55 inches. For the soils in the area, SCS hydrologic soil classifications are delineated by Cline (1988) as in Fig. 21.
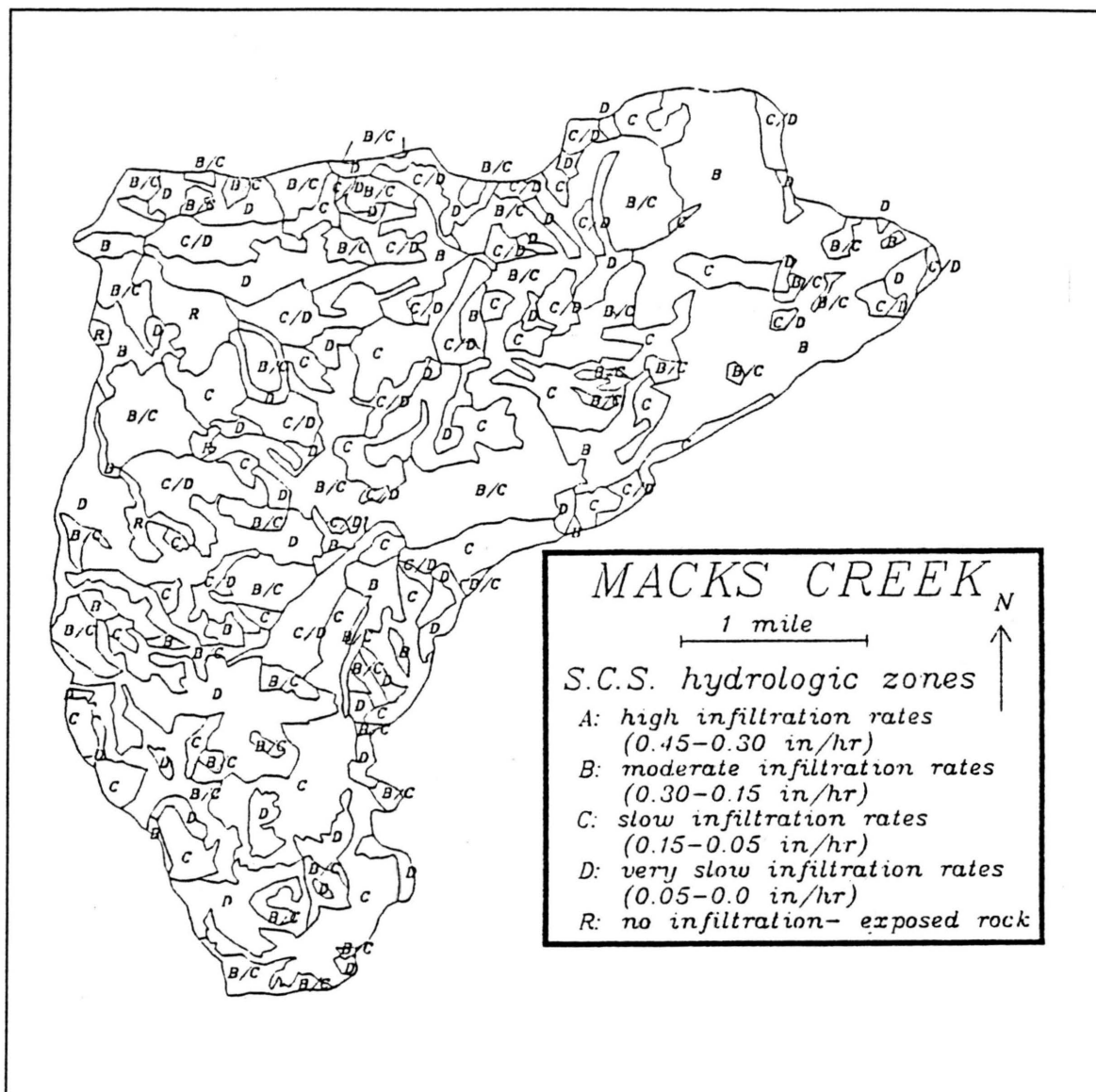
Figure 21. SCS Soil Zone Delineations on Macks Creek

The SCS soil types for this area are numbered as B = 1, B/C = 2, C = 3, C/D = 4, D = 5, and R = 6. The dominant soil type (number) was determined for all 1390 grids and installed in SOIL.DAT. Infiltration parameters for each soil type was roughly estimated from Table 1. For example, Soil B (number 1) was categorized as having moderate infiltration rates, between 0.3 iph to 0.15 iph. This rate is actually the steady state infiltration rate, the same as hydraulic conductivity at normal saturation (K_s). If an average K_s of 0.225 iph (0.57 cm/hr) is chosen, then the nearest K_s in Table 1 would be 0.65 cm/hr for silt loam. As a result, soil B was estimated to be silty loam as defined by its infiltration characteristics, and then the other two parameters (θ_e and H_f) were deduced from the same table. The results have been summarized in the following table.

Table 2. Soil Texture Classifications for Macks Creek

Soil Number	SCS soil Type	Estimated Soil Type	K_s (cm/h)	θ_e	H_f (cm)	Estimated M_d
1	B	silty loam	0.65	0.486	16.68	0.35
2	B/C	loam	0.34	0.434	8.89	0.3
3	C	sandy clay loam	0.15	0.330	21.85	0.3
4	C/D	silty clay loam	0.10	0.432	27.3	0.3
5	D	sandy clay	0.05	0.321	23.9	0.3
6	R	exposed rock	0.0	-	-	-

Since there was no information on initial moisture for each soil, this parameter had to be calibrated. Due to another storm occurring on August 22, 1965, just one day before the storm under analysis, the soil condition could not be entirely dry. The estimated soil moisture deficits are shown in Table 2.

Once the mesh has been overlaid on the watershed, the channel paths can be followed and the channel elements determined. There was no specific data on channel size, width and depth, except some photographs at the outlet and eyewitness accounts. Therefore, number of channel orders, as well as size and roughness of each channel had to be estimated. Some other parameters also needed to be estimated, such as overland Manning's n. The general variables used in part of DATA1 are given as :

Line #1 :
    M = total number of rows = 53
    N = total number of columns = 53
    W = grid size = 151.159 m
    NMAN = number of overland Manning n roughness type = 1
    SDEP = overland detention storage = 0.0

Line #2 :
    DT = simulation time step = 30 sec
    NITER = total number of iterations = 480

NITRN = rainfall duration divided by DT = 240

NPRN = number of time steps between runoff discharge writings in output
file = 1

NPLT = number of time steps to update graphics display = 1

Line #3 :

JOUT = outlet row number = 10

KOUT = outlet column number = 52

SOUT = uniform flow bed slope at outlet = 0.015

QMAX = maximum roughly predicted discharge to be used for graphics = 120
cfs

WCHOUT = channel width at outlet = 10 m

DCHOUT = channel depth at outlet = 10 m

RMANOUT = Manning's channel roughness coefficient at outlet = 0.03

Line #4 :

INDEXINF = infiltration index = 1

NSOIL = number of soils with different infiltration parameters = 6

Line #5 :

NCHN = total number of channels = 23

MAXCHN = maximum allowable number of channel elements for any
channel = 16

Line #6 :

IELPLT = elevation plotting index = 1

ISOILPLT = soil plotting index = 1

IDEPPLT = dynamic window plotting index = 1

Line #7 :

IRAIN = rainfall index = 1

Line #8 :

NRG = number of raingages = 8

NREAD = ratio between raingage rainfall data time step and DT = 4

The remainder of DATA1 is filled with location of raingages, Manning n, and infiltration parameters. The average Manning n for overland flow was 0.06. The observed and simulated hydrographs are shown in Fig. 22.
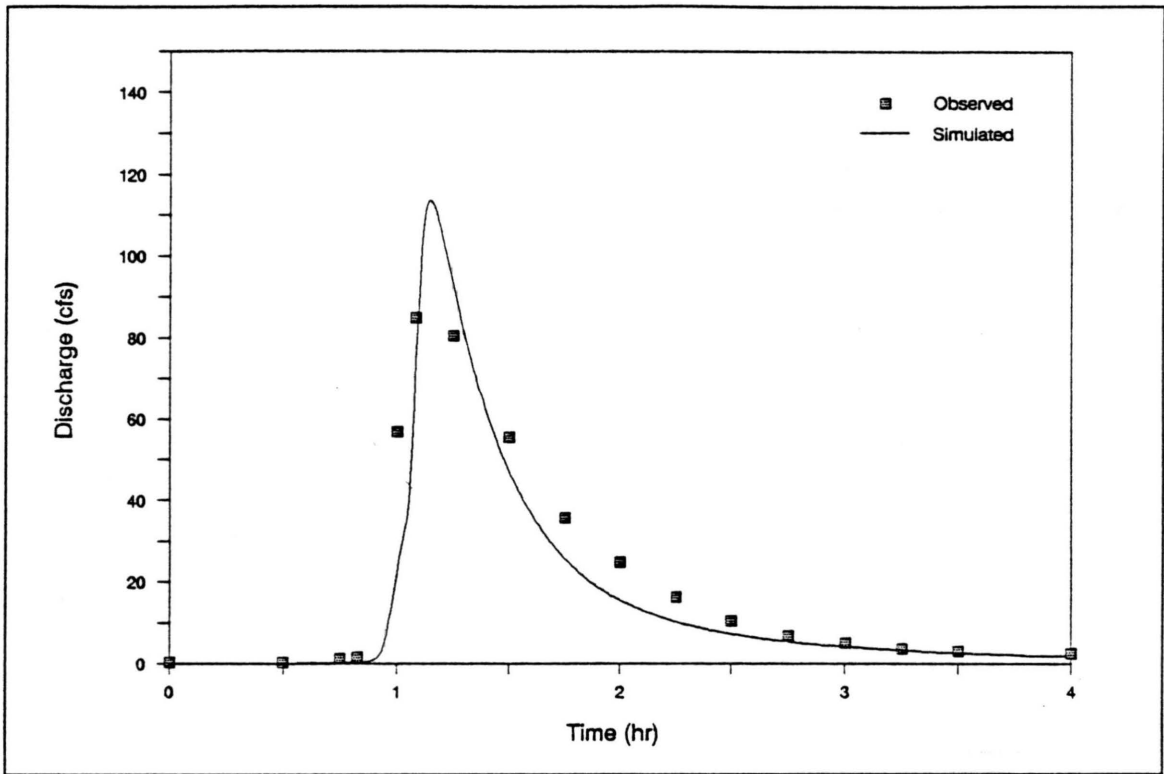
Figure 22. Simulated and Observed Outflow Hydrograph

7. SUMMARY

This manual explains the basics of a two-dimensional distributed rainfall-runoff model for the simulation and analysis of spatially and temporally varied rainstorms and basin characteristics. The primary features of the model include a two-dimensional diffusive wave overland flow routing, a one-dimensional diffusive wave channel routing, and the Green-Ampt infiltration scheme. The model uses square grid elements, each of which is assumed homogeneous in all aspects. However, spatial variations are allowed from one grid to another. For each time step, the existing overland surface depth, including that of rainfall depth over the time step, may be first diminished by the amount controlled by the infiltration capacity of the soil at that time. Then the remaining overland surface depth, if any, is processed through overland flow routing followed by channel routing. The backwater effects through channel networks are considered, as well as the disturbances produced when channels spill over to the floodplains. For all of the case studies reported in Chapter 6, the model simulation time on a personal computer IBM PS2/Model 80 has been much shorter than real time. The model has also been evaluated with several case studies and the results has been encouraging.

As a valuable tool, the model is planned to carry out the research on effects of spatially varied watershed characteristics, spatially varied rainfall, and temporally varied rainfall due to moving rainstorms. The model is currently being used to determine the watershed time to equilibrium. An important potential application for the model is real-time flood forecasting, especially when coupled with remote data acquisition systems.

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Appendix A

Program Listing

```
C-MODEL VERSION 1.0, WRITTEN IN FORTRAN BY BAHRAM SAGHAFIAN, SPRING 1991
C       PROGRAM CASC2D
C       ==============
$NOLIST
        INCLUDE 'FGRAPH.FI'
        INCLUDE 'FGRAPH.FD'
$LIST
        INTEGER*1  ISHP(53,53),IMAN(53,53),ISOIL(53,53)
        COMMON /BLOK1/ E(53,53),H(53,53),RINT(53,53),VINF(53,53)
        COMMON /BLOK2/ DQOV(53,53),DQCH(53,53),HCH(53,53),XRG(8),YRG(8),
     +                 RRG(8),PMAN(10),PINF(10,3),ICHN(23,16,2),CHP(23,3)
        RECORD /videoconfig/ screen
        COMMON screen
C
        CALL GETTIM(IHR,IMIN,ISEC,I100)
        CALL FONTS()
C       ----------------------------------------------------------------
C       OPENING FILES
C       ----------------------------------------------------------------
        OPEN(UNIT=21,FILE='SHAP.DAT')
        OPEN(UNIT=22,FILE='ELAVG.DAT')
        OPEN(UNIT=23,FILE='RAIN.DAT')
        OPEN(UNIT=24,FILE='SOIL.DAT')
        OPEN(UNIT=25,FILE='DATA1')
        OPEN(UNIT=26,FILE='CHN.DAT')
        OPEN(UNIT=27,FILE='OUT.PRN')
        OPEN(UNIT=28,FILE='IMAN.DAT')
C       ----------------------------------------------------------------
        WRITE(27,'('' Started at '',I2,'':'',I2,'':'',I2)')IHR,IMIN,ISEC
        WRITE(27,222)
C       ----------------------------------------------------------------
C       READING DATA
C       ----------------------------------------------------------------
        READ(25,*) M,N,W,NMAN,SDEP
        READ(25,*) DT,NITER,NITRN,NPRN,NPLT
        READ(25,*) JOUT,KOUT,SOUT,qmax,WCHOUT,DCHOUT,RMANOUT
        READ(25,*) INDEXINF,NSOIL
        READ(25,*) NCHN,MAXCHN
        READ(25,*) IELPLT,ISOILPLT,IDEPPLT
        READ(25,*) IRAIN
C
        IF(IRAIN.EQ.0) READ(25,*) CRAIN
        IF(IRAIN.EQ.1) READ(25,*) NRG,NREAD
        IF(IRAIN.EQ.1) READ(25,*) (XRG(L),YRG(L),L=1,NRG)
C
        READ(25,*) (PMAN(J),J=1,NMAN)
        IF(INDEXINF.EQ.1) READ(25,*) ((PINF(J,K),K=1,3),J=1,NSOIL)
C
        IF(NCHN.NE.0) READ(26,*) ((CHP(L,K),K=1,3),L=1,NCHN)
        IF(NCHN.NE.0) READ(26,128) (((ICHN(L,J,K),J=1,MAXCHN),
     +                              K=1,2),L=1,NCHN)
 128    FORMAT(/16I3/16I3)
C       ----------------------------------------------------------------
C       READING SHAP MATIX AND ELEVATIONS AND INITIALIZATION
C       ----------------------------------------------------------------
```

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```fortran
          DO 150 J=1,M
              DO 150 K=1,N
                  READ(21,*) ISHP(J,K)
                  IF(ISHP(J,K).EQ.0) GO TO 150
                  READ(22,*) E(J,K)
                  E(J,K)=E(J,K)/3.28
                  IF(NMAN.EQ.1) THEN
                      IMAN(J,K)=1
                  ELSE
                      READ(28,*) IMAN(J,K)
                  ENDIF
C
                  IF(NSOIL.EQ.1) THEN
                      ISOIL(J,K)=1
                  ELSE
                      READ(24,*) ISOIL(J,K)
                  ENDIF
C
                  H(J,K)=0.
                  HCH(J,K)=0.
                  DQOV(J,K)=0.
                  DQCH(J,K)=0.
                  VINF(J,K)=0.
  150 CONTINUE
C     ---------------------------------------------
      DO 160 IC=1,NCHN,1
          DO 175 L=1,MAXCHN,1
              J=ICHN(IC,L,1)
              K=ICHN(IC,L,2)
              IF(J.LE.0) GO TO 160
              ISHP(J,K)=2
  175     CONTINUE
  160 CONTINUE
C     -------------------------------------------------
      IF(IELPLT.EQ.1)    CALL ELPLT(ISHP,E)
      IF(ISOILPLT.EQ.1)  CALL SOILPLT(ISHP,ISOIL,NSOIL)
C     -------------------------------------------------
      VIN=0.
      VOUT=0.
      VSUR=0.
      VINFTOT=0.
      RINDEX=1.
C     ---------------------------------------------
C     TIME DO LOOP
C     ---------------------------------------------
      DO 10 I=1,NITER
          IF(IDEPPLT.EQ.0)  WRITE(*,*)I
          ICALL=0
          IF(I.GT.NITRN)  RINDEX=0.
          IF(I.LE.NITRN.AND.IRAIN.EQ.1)  THEN
              IF(((I-1)/NREAD)*NREAD.EQ.(I-1)) THEN
                  ICALL=1
                  READ(23,124) (RRG(L),L=1,NRG)
  124             FORMAT(8F9.3)
              ENDIF
```

```
        ENDIF
C       ---------------------UPDATE OVERLAND DEPTH--------------------
        DO 1 J=1,M
           DO 1 K=1,N
              IF(ISHP(J,K).EQ.0) GO TO 1
              IF(IRAIN.EQ.0) THEN
                 RINT(J,K)=CRAIN
              ELSE
                 IF(ICALL.EQ.1) CALL RAIN(J,K,NRG,XRG,YRG,RRG,RINT)
              ENDIF
              IF(I.GT.NITRN) RINT(J,K)=0.
C
              HOV=DQOV(J,K)*DT/(W*W)
              HOV=HOV+H(J,K)+RINDEX*RINT(J,K)*DT
              IF(HOV.LT.0) GO TO 170
              IF(INDEXINF.EQ.1)CALL INFILT(J,K,DT,ISOIL,VINF,PINF,HOV)
              H(J,K)=HOV
              DQOV(J,K)=0.
              VIN=VIN+RINDEX*RINT(J,K)*DT*W*W
              IF(I.EQ.NITER) VINFTOT=VINFTOT+VINF(J,K)*W*W
              IF(I.EQ.NITER.AND.ISHP(J,K).EQ.1) VSUR=VSUR+H(J,K)*W*W
   1    CONTINUE
C       --------------------UPDATE CHANNEL DEPTH---------------------
        DO 2 IC=1,NCHN,1
           DO 3 L=1,MAXCHN,1
              J=ICHN(IC,L,1)
              K=ICHN(IC,L,2)
              JJ=ICHN(IC,L+1,1)
              IF(J.LE.0) GO TO 2
              IF(JJ.LT.0) GO TO 2
              WCH=CHP(IC,1)
              DCH=CHP(IC,2)
              DHCH=DQCH(J,K)*DT/(W*WCH)
              HCH(J,K)=HCH(J,K)+DHCH
              IF(H(J,K).GT.SDEP) THEN
                 HCH(J,K)=HCH(J,K)+(H(J,K)-SDEP)*W/WCH
                 H(J,K)=SDEP
              ENDIF
              HTOP=DCH+H(J,K)
              IF(HCH(J,K).GT.HTOP) THEN
                 DH=(HCH(J,K)-HTOP)*WCH/W
                 H(J,K)=H(J,K)+DH
                 HCH(J,K)=HCH(J,K)-DH
              ENDIF
              IF(HCH(J,K).LT.0) GO TO 170
              DQCH(J,K)=0.
              IF(I.EQ.NITER) VSUR=VSUR+HCH(J,K)*W*WCH+H(J,K)*W*W
   3       CONTINUE
   2    CONTINUE
C       --------------------OVERLAND FLOW ROUTING--------------------
  11    DO 20 J=1,M
           DO 30 K=1,N
              IF(ISHP(J,K).EQ.0) GO TO 30
              DO 40 L=-1,0,1
                 JJ=J+L+1
```

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```
               KK=K-L
               IF(JJ.GT.M.OR.KK.GT.N.OR.ISHP(JJ,KK).EQ.0) GO TO 40
               CALL OVRL(W,IMAN,PMAN,SDEP,J,K,JJ,KK,E,H,DQOV)
  40        CONTINUE
  30      CONTINUE
  20    CONTINUE
C         ---------------------CHANNEL FLOW ROUTING---------------------
        DO 50 IC=1,NCHN,1
           WCH=CHP(IC,1)
           DCH=CHP(IC,2)
           RMANCH=CHP(IC,3)
           DO 60 L=1,MAXCHN-1,1
              J=ICHN(IC,L,1)
              K=ICHN(IC,L,2)
              JJ=ICHN(IC,L+1,1)
              KK=ICHN(IC,L+1,2)
              JJJ=ICHN(IC,L+2,1)
              IF(JJ.LE.0) GO TO 50
              CALL CHNCHN(NCHN,W,WCH,DCH,RMANCH,
     +                    J,K,JJ,KK,JJJ,E,HCH,ICHN,CHP,DQCH)
  60        CONTINUE
  50    CONTINUE
C         --------------------OUTFLOW DISCHARGE---------------------
           HOUT=H(JOUT,KOUT)
           ALFA=SQRT(SOUT)/PMAN(IMAN(JOUT,KOUT))
           QOUTOV=0.
           IF(HOUT.GT.SDEP) QOUTOV=W*ALFA*((HOUT-SDEP)**1.667)
           H(JOUT,KOUT)=HOUT-QOUTOV*DT/(W*W)
C
           HOUT=HCH(JOUT,KOUT)
           WPOUT=WCHOUT+2.*HOUT
           IF(HOUT.GT.DCHOUT) WPOUT=WCHOUT+2.*DCHOUT
           AREAOUT=WCHOUT*HOUT
           ALFA=SQRT(SOUT)/RMANOUT
           QOUTCH=ALFA*(AREAOUT**1.6667)/(WPOUT**0.6667)
           HCH(JOUT,KOUT)=HOUT-QOUTCH*DT/(W*WCHOUT)
           QOUT=QOUTOV+QOUTCH
           VOUT=VOUT+QOUT*DT
C         ------------------------------------------------------------
        IF(I.EQ.1) QOLD=0.0
        IF((IDEPPLT.EQ.1).AND.(((I-1)/NPLT)*NPLT).EQ.I-1)
     +      CALL DEPPLT(I,NPLT,ISHP,RINT,NITRN,IRAIN,ICALL,VINF,
     +      INDEXINF,H,HCH,niter,dt,qout,qold,qmax)
        IF(((I-1)/NPLT)*NPLT.EQ.I-1) qold = qout
        IF((I/NPRN)*NPRN.EQ.I) WRITE(27,111) I*DT/60.,QOUT
  10    CONTINUE
C     ------------------------------------------------------------
C     END OF TIME DO LOOP
C     ------------------------------------------------------------
      WRITE(27,113) VIN,VOUT,VSUR,VINFTOT
      GO TO 172
 170  WRITE(27,171) J,K,I*DT,HOV
 172  CONTINUE
      CALL GETTIM(IHR,IMIN,ISEC,I100)
      WRITE(27,'('' Stopped at '',I2,'':'',I2,'':'',I2)')IHR,IMIN,ISEC
```

```
C        ------------------------------------------------------------
  222   FORMAT(//' TIME(MIN)  DISCHARGE(m3/s)'/)
  111   FORMAT(2X,F7.2,F14.5)
  113   FORMAT(//' VOLUME IN IN m3=',F15.6/' VOLUME OUT IN m3=',F15.6
       +    /' SURFACE VOLUME IN m3=',F15.6/' VOLUME INFILTRATED IN
       +    m3=',F15.6)
  171   FORMAT(/'PROGRAM STOPPED FOR NEGATIVE DEPTH',2I4,F10.1,F12.8)
C        ------------------------------------------------------------
        IF(IDEPPLT.EQ.1)  read(*,*)
        idummy=setvideomode( $DEFAULTMODE)
        STOP
        END
C
C        =======================================
        SUBROUTINE RAIN(J,K,NRG,XRG,YRG,RRG,RINT)
C        =======================================
C        subroutine to calculate rainfall intensity for each element
C
        DIMENSION XRG(NRG),YRG(NRG),RINT(53,53),RRG(8)
C
        RINT(J,K)=0.
        TOTDIST=0.
        TOTRAIN=0.
C
        DO 1 L=1,NRG
            REALJ=J
            REALK=K
            DIST=SQRT((REALJ-YRG(L))**2+(REALK-XRG(L))**2)
            IF(DIST.LT.1E-5) THEN
                RINT(J,K)=RRG(L)
                GO TO 2
            ENDIF
            TOTDIST=TOTDIST+1./(DIST**2)
            TOTRAIN=TOTRAIN+RRG(L)/(DIST**2)
  1     CONTINUE
        RINT(J,K)=TOTRAIN/TOTDIST
C----->       UNIT CHANGE FROM cm/hr TO m/s
  2     RINT(J,K)=RINT(J,K)*0.01/3600.
        RETURN
        END
C
C        ============================================
        SUBROUTINE INFILT(J,K,DT,ISOIL,VINF,PINF,HOV)
C        ============================================
C        subroutine to calculate infiltration rate
C
        INTEGER*1  ISOIL(53,53)
        DIMENSION  VINF(53,53),PINF(10,3)
C
        IINF=ISOIL(J,K)
        HYDCON=PINF(IINF,1)
        CS=PINF(IINF,2)
        SMD=PINF(IINF,3)
C
        P1=HYDCON*DT-2.*VINF(J,K)
```

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```
      P2=HYDCON*(VINF(J,K)+CS*SMD)
      RINF=(P1+SQRT(P1**2+8.*P2*DT))/(2.*DT)
      IF((HOV/DT).LE.RINF) THEN
          RINF=HOV/DT
          HOV=0
      ELSE
         HOV=HOV-RINF*DT
      ENDIF
      VINF(J,K)=VINF(J,K)+RINF*DT
      RETURN
      END
C
C     =======================================================
      SUBROUTINE OVRL(W,IMAN,PMAN,SDEP,J,K,JJ,KK,E,H,DQOV)
C     =======================================================
C     subroutine for overland flow routing
C
      DIMENSION   E(53,53),H(53,53),DQOV(53,53),PMAN(10)
      INTEGER*1   IMAN(53,53)
      DATA        A/1./
C
      S0=(E(J,K)-E(JJ,KK))/W
      DHDX=(H(JJ,KK)-H(J,K))/W
      SF=S0-DHDX+1E-30
      IF(ABS(SF).LT.1E-20) SF=1E-20
      HH=H(J,K)
      RMAN=PMAN(IMAN(J,K))
      IF(SF.LT.0) HH=H(JJ,KK)
      IF(SF.LT.0) RMAN=PMAN(IMAN(JJ,KK))
      IF(HH.LT.SDEP) RETURN
      ALFA=(ABS(SF)**0.5)/RMAN
      DQQ=SIGN(A,SF)*W*ALFA*((HH-SDEP)**1.667)
      DQOV(J,K)=DQOV(J,K)-DQQ
      DQOV(JJ,KK)=DQOV(JJ,KK)+DQQ
      RETURN
      END
C
C     =======================================================
      SUBROUTINE CHNCHN(NCHN,W,WCH,DCH,RMANCH,
     +                  J,K,JJ,KK,JJJ,E,HCH,ICHN,CHP,DQCH)
C     =======================================================
C     subroutine for channel routing
C
      DIMENSION E(53,53),HCH(53,53),ICHN(23,16,2),CHP(23,3),DQCH(53,53)
      DATA      A/1./
C
      S0=(E(J,K)-DCH-E(JJ,KK)+DCH)/W
      DHDX=(HCH(JJ,KK)-HCH(J,K))/W
      SF=S0-DHDX+1E-30
      IF(ABS(SF).LT.1E-20) SF=1E-20
      HH=HCH(J,K)
      IF(SF.LT.0)  THEN
         IF(JJJ.LT.0)  THEN
             DO 5  IIC=1,NCHN,1
```

```fortran
                IF(JJ.EQ.ICHN(IIC,1,1).AND.KK.EQ.ICHN(IIC,1,2)) THEN
                    S0=(E(J,K)-DCH-E(JJ,KK)+CHP(IIC,2))/W
                    DHDX=(HCH(JJ,KK)-HCH(J,K))/W
                    SF=S0-DHDX+1E-30
                    IF(ABS(SF).LT.1E-20) SF=1E-20
                    IF(SF.GT.0) GO TO 6
                    WCH=CHP(IIC,1)
                    DCH=CHP(IIC,2)
                    RMANCH=CHP(IIC,3)
                    HH=HCH(JJ,KK)
                    GO TO 6
                ENDIF
5             CONTINUE
          ENDIF
      ENDIF
6     WP=WCH+2.*HH
      IF(HH.GT.DCH) WP=WCH+2.*DCH
      AREA=WCH*HH
      DQ=SIGN(A,SF)*(SQRT(ABS(SF))/RMANCH)*(AREA**1.6667)/(WP**0.6667)
      DQCH(J,K)=DQCH(J,K)-DQ
      DQCH(JJ,KK)=DQCH(JJ,KK)+DQ
      RETURN
      END
C
C     graphics routine
C     =============================
      LOGICAL FUNCTION fourcolors()
C     =============================
$NOLIST
      INCLUDE 'FGRAPH.FD'
$LIST
      INTEGER*2 dummy
      RECORD /videoconfig/ screen
      COMMON screen
C
      CALL getvideoconfig( screen )
      if ((screen.mode.ne.3).and.(screen.mode.ne.7)) then
         fourcolors = .true.
         return
      endif
      SELECT CASE( screen.adapter )
            CASE( $EGA, $OEGA)
                dummy=setvideomode( $ERESCOLOR)
            CASE( $VGA )
                dummy=setvideomode( $VRES16COLOR)
            CASE DEFAULT
                dummy=0
      END SELECT
      CALL getvideoconfig( screen )
      fourcolors=.TRUE.
      IF(dummy.EQ.0) fourcolors=.FALSE.
      END
C
C     ========================
      SUBROUTINE ELPLT(ishp,e)
```

```
C       ==========================
C       subroutine to plot elevation map
C
$NOLIST
        INCLUDE 'FGRAPH.FD'
$LIST
C
        CHARACTER*80  buffer
        INTEGER*2 dummy,icolor
        INTEGER*1  ishp(53,53),ielcol(10)
        LOGICAL fourcolors
        EXTERNAL fourcolors
        RECORD /wxycoord/ wxy
        RECORD /videoconfig/ screen
        COMMON screen
        DIMENSION e(53,53),rel(10)
        DATA    nel/10/
C
        OPEN(UNIT=30,FILE='elcol.dat')
C
        IF( fourcolors() ) THEN
          READ(30,33) (ielcol(ic),rel(ic),ic=1,nel)
  33      format(i3,f15.0)
          CALL clearscreen( $GCLEARSCREEN)
          nx=screen.numxpixels
          ny=screen.numypixels
          CALL setviewport(0,0,ny-1,ny-1)
          dummy=setwindow(.FALSE.,-3.,-3.,56.,56.)
          dummy=setcolor(15)
          dummy=rectangle_w( $GBORDER,-3.,-3.,56.,56.)
C
          dummy=setfont('t''roman''h20w19b')
          dummy=setcolor(10)
          call moveto_w(-2.9,-2.5,wxy)
          call outgtext("Macks Creek Elevation Map")
C       -------------------------------
C       create color bars for elevation
C       -------------------------------
          dummy=setfont('t''roman''h12w12b')
          CALL moveto_w( 42.,30.5,wxy)
          dummy=setcolor(15)
          call outgtext("Meters")
          dummy=setfont('t''modern''h12w12b')
          DO  20 II=1,nel
              dummy=setcolor(ielcol(II))
              dummy=rectangle_w( $GFILLINTERIOR,50.,53.-2*II,53.,55-2*II)
              dummy=setcolor(15)
              CALL moveto_w( 40.,53.5-2.*II,wxy)
              write(buffer,200) rel(II)
              call outgtext(buffer)
  20      CONTINUE
  200     format('',f5.0)
C
          dummy=setcolor(14)
          DO 10 j=1,53
```

```
              DO 10 k=1,53
                  IF(ishp(j,k).EQ.0) GO TO 10
                  ee=e(j,k)
                  IF(ee.LT.rel(1))                    icolor=ielcol(1)
                  IF(ee.GE.rel(1).AND.ee.LT.rel(2))icolor=ielcol(2)
                  IF(ee.GE.rel(2).AND.ee.LT.rel(3))icolor=ielcol(3)
                  IF(ee.GE.rel(3).AND.ee.LT.rel(4))icolor=ielcol(4)
                  IF(ee.GE.rel(4).AND.ee.LT.rel(5))icolor=ielcol(5)
                  IF(ee.GE.rel(5).AND.ee.LT.rel(6))icolor=ielcol(6)
                  IF(ee.GE.rel(6).AND.ee.LT.rel(7))icolor=ielcol(7)
                  IF(ee.GE.rel(7).AND.ee.LT.rel(8))icolor=ielcol(8)
                  IF(ee.GE.rel(8).AND.ee.LT.rel(9))icolor=ielcol(9)
                  IF(ee.GT.rel(9))                    icolor=ielcol(10)
                  dummy=setcolor(icolor)
                  dummy=rectangle_w( $GFILLINTERIOR,k,j,k+1,j+1)
   10         CONTINUE
          CALL setviewport(0,0,nx-1,ny-1)
C
          READ(*,*)          ! WAIT FOR ENTER TO BE PRESSED
C
      ELSE
          WRITE(*,*) 'THIS PROGRAM REQUIRES EGA OR VGA CARDS.'
      ENDIF
C
      END
C
C     =====================================
      SUBROUTINE SOILPLT(ishp,isoil,nsoil)
C     =====================================
C     subroutine to plot soil map
C
$NOLIST
      INCLUDE 'FGRAPH.FD'
$LIST
C
      INTEGER*2 dummy,icolor
      INTEGER*1  ishp(53,53),isoil(53,53),isoilcol(6)
      LOGICAL fourcolors
      EXTERNAL fourcolors
      RECORD /wxycoord/ wxy
      RECORD /videoconfig/ screen
      COMMON screen
      CHARACTER*3 STYPE(6)
      DATA STYPE/'B','B/C','C','C/D','D','R'/
C
      OPEN(UNIT=31,FILE='soilcol.dat')
C
      IF( fourcolors() ) THEN
        READ(31,*) (isoilcol(ic),ic=1,nsoil)
        CALL clearscreen( $GCLEARSCREEN)
        nx=screen.numxpixels
        ny=screen.numypixels
        CALL setviewport(0,0,ny-1,ny-1)
        dummy=setwindow(.FALSE.,-3.,-3.,56.,56.)
```

```fortran
           dummy=setcolor(15)
           dummy=rectangle_w( $GBORDER,-3.,-3.,56.,56.)
C
           dummy=setfont('t''roman''h20w19b')
           dummy=setcolor(14)
           call moveto_w(-2.9,-2.5,wxy)
           call outgtext("Macks Creek Soil Type Map")
           dummy=setfont('t''roman''h12w12b')
           dummy=setcolor(15)
           call moveto_w(37.,29.,wxy)
           call outgtext("SCS Soil Zones")
C      --------------------------
C      create color bars for soils
C      --------------------------
           DO  20 II=1,6
               dummy=setcolor(isoilcol(II))
               dummy=rectangle_w( $GFILLINTERIOR,50.,30.+2*II,53.,32.+2*II)
               dummy=setcolor(15)
               CALL moveto_w( 44.,30.5+2*II,wxy)
               CALL outgtext(STYPE(II))
   20      CONTINUE
C
           dummy=setcolor(14)
           DO 10 j=1,53
             DO 10 k=1,53
                 IF(ishp(j,k).EQ.0) GO TO 10
                 icolor=8
                 IF(isoil(j,k).EQ.1) icolor=isoilcol(1)
                 IF(isoil(j,k).EQ.2) icolor=isoilcol(2)
                 IF(isoil(j,k).EQ.3) icolor=isoilcol(3)
                 IF(isoil(j,k).EQ.4) icolor=isoilcol(4)
                 IF(isoil(j,k).EQ.5) icolor=isoilcol(5)
                 IF(isoil(j,k).EQ.6) icolor=isoilcol(6)
                 dummy=setcolor(icolor)
                 dummy=rectangle_w( $GFILLINTERIOR,k,j,k+1,j+1)
   10      CONTINUE
           CALL setviewport(0,0,nx-1,ny-1)
C
           READ(*,*)            ! WAIT FOR ENTER TO BE PRESSED
C
         ELSE
             WRITE(*,*) 'THIS PROGRAM REQUIRES EGA OR VGA CARDS.'
         ENDIF
C
         END
C
C      ==============================================================
         SUBROUTINE DEPPLT(i,nplt,ishp,rint,nitrn,irain,icall,vinf,
      +                    indexinf,h,hch,niter,dt,qout,qold,qmax)
C      ==============================================================
C      subroutine to plot rainfall, cummulative infiltration, and surface
C      depth.
C
$NOLIST
         INCLUDE 'FGRAPH.FD'
```

61

```fortran
$LIST
C
      CHARACTER*80  buffer
      INTEGER*1  ishp(53,53),idepcol(10),iinfcol(10),irancol(10)
      INTEGER*2 dummy,icolor
      DOUBLE PRECISION xx,yy
      LOGICAL fourcolors
      EXTERNAL fourcolors
      RECORD /wxycoord/ wxy
      RECORD /videoconfig/ screen
      COMMON screen
      DIMENSION   rint(53,53),vinf(53,53),h(53,53),hch(53,53)
      DIMENSION   rdep(10),rinfl(10),rrain(10)
      DATA        ndiv/4/
C
      OPEN(UNIT=32,FILE='depcol.dat')
      OPEN(UNIT=33,FILE='infcol.dat')
      OPEN(UNIT=34,FILE='rancol.dat')
C
C----------------------------------------------------------------------
      IF(i.EQ.1) THEN
          IF(.not. fourcolors()) THEN
              WRITE(*,*) 'THIS PROGRAM REQUIRES EGA OR VGA CARDS.'
              RETURN
          ENDIF
          READ(32,101) (idepcol(ic),rdep(ic),ic=1,10)
          READ(33,101) (iinfcol(ic),rinfl(ic),ic=1,10)
          READ(34,101) (irancol(ic),rrain(ic),ic=1,10)
  101     format (i3,f15.0)
C         ------------------------------------------------
          CALL clearscreen( $GCLEARSCREEN)
          nx=screen.numxpixels
          ny=screen.numypixels
          dummy=setcolor(15)
          dummy=setwindow(.FALSE.,0.,0.,127.*2,95.*2)
          dummy=setcolor(12)
          dummy=rectangle_w( $GFILLINTERIOR,2.*2,3.*2,62.*2,62.*2)
          dummy=setcolor(12)
          dummy=rectangle_w( $GFILLINTERIOR,65.*2,3.*2,125.*2,62.*2)
          dummy=setcolor(12)
          dummy=rectangle_w( $GFILLINTERIOR,2.*2,62.*2,30.5*2,95.*2)
          dummy=setcolor(15)
          dummy=rectangle_w( $GBORDER,30.5*2,62.*2,125.*2,95.*2)
          dummy=setcolor(15)
          dummy=rectangle_w( $GFILLINTERIOR,100.*2,62.*2,125.*2,72.*2)
C         -------------------------------------------------
          dummy=setcolor(14)
          call moveto_w(2*36.,2*92.,wxy)
          dummy=lineto_w(2.*124.,2.*92.)
          call moveto_w(2*36.,2*92.,wxy)
          dummy=lineto_w(2.*36.,2.*64.)
C
          dummy=setcolor(14)
          DO 81 kj=1,ndiv,1
             call setlinestyle(#ffff)
```

```
                call moveto_w(2*35.5,2*(92.-kj*28./ndiv),wxy)
                dummy=lineto_w(2.*36.5,2.*(92.-kj*28./ndiv))
                call moveto_w(2*(36.+kj*88./ndiv),2.*92.5,wxy)
                dummy=lineto_w(2.*(36.+kj*88./ndiv),2.*91.5)
                call setlinestyle(#8000)
                call moveto_w(2*36.,2*(92.-kj*28./ndiv),wxy)
                dummy=lineto_w(2.*124.,2.*(92.-kj*28./ndiv))
    81          CONTINUE
                call setlinestyle(#ffff)
    C           -----------------------------------------------------------
    83          dummy=setfont('t''modern''h6w6b')
                dummy=setcolor(14)
                call moveto_w(2*35.5,2*93.,wxy)
                write(buffer,201) 0
                call outgtext(buffer)
                call moveto_w(2*34.,2*90.5,wxy)
                write(buffer,201) 0
    201         format(i1)
    C
                call outgtext(buffer)
                call moveto_w(2*120.,2*93.,wxy)
                write(buffer,203) int(niter*dt/60.)
                call outgtext(buffer)
                call moveto_w(2*31.5,2*64.,wxy)
                write(buffer,200) int(qmax)
                call outgtext(buffer)
    200         format(i3)
    203         format(i4)
    C           -------------------------------------------------
                dummy=setfont('t''modern''h16w16b')
                dummy=setcolor(14)
                call moveto_w(2*33.,2*0.,wxy)
                call outgtext("Macks Creek Watershed")
                call moveto_w(2*32.8,2*0.,wxy)
                call outgtext("Macks Creek Watershed")
                dummy=setfont('t''modern''h13w13b')
                dummy=setcolor(10)
                call moveto_w(2*7.,2*3.5,wxy)
                call outgtext("Rainfall Intensity (cm/h)")
                call moveto_w(2*6.85,2*3.5,wxy)
                call outgtext("Rainfall Intensity (cm/h)")
                dummy=setcolor(10)
                call moveto_w(2*77.,2*3.5,wxy)
                call outgtext("Average Depth (m)")
                call moveto_w(2*76.8,2*3.5,wxy)
                call outgtext("Average Depth (m)")
                dummy=setfont('t''modern''h11w8b')
                dummy=setcolor(10)
                call moveto_w(2*2.3,2*63.,wxy)
                call outgtext("Infiltration Depth (m)")
    C           ---------------------------------------------------
                dummy=setfont('t''modern''h9w8b')
                dummy=setcolor(12)
                call moveto_w(2*74.,2*93.,wxy)
                call outgtext("Time (min)")
```

```fortran
        call moveto_w(2*31.5,2*76.,wxy)
        call outgtext(" Q")
        call moveto_w(2*31.5,2*79.,wxy)
        call outgtext("cms")
c
        dummy=setcolor(0)
        dummy=rectangle_w( $GFILLINTERIOR,101.*2,63.*2,124.*2,71.*2)
        dummy=setcolor(11)
        dummy=setfont('t''modern''h12w8b')
        call moveto_w(2*102.,2*64.,wxy)
        call outgtext("Time = ")
        call moveto_w(2*102.,2*67.,wxy)
        call outgtext("Qout = ")
c       ----------------------------------------
c       create color bars for depth and rainfall
c       ----------------------------------------
        DO  20 II=1,10
           dummy=setfont('t''modern''h8w6b')
           dummy=setcolor(irancol(II))
           dummy=rectangle_w( $GFILLINTERIOR,2*53.,2*(60.-3.*II)
     +                  ,2*58.,2*(62.-3.*II))
           dummy=setcolor(idepcol(II))
           dummy=rectangle_w( $GFILLINTERIOR,2*116.,2*(60.-3.*II)
     +                  ,2*121.,2*(62.-3.*II))
            dummy=setcolor(iinfcol(II))
            dummy=rectangle_w( $GFILLINTERIOR,53.,2*(94.-1.5*II)
     +                  ,57.,2*(95.-1.5*II))
           dummy=setcolor(15)
           call moveto_w(2*45.5,2*(60.-3.*II),wxy)
           write(buffer,102) rrain(II)
           call outgtext(buffer)
c
           call moveto_w(2*107.,2*(60.-3.*II),wxy)
           write(buffer,105) rdep(II)
           call outgtext(buffer)
c
            dummy=setfont('t''modern''h6w4b')
            call moveto_w(41.5,2.*(94.1-1.5*II),wxy)
            write(buffer,105) rinfl(II)
            call outgtext(buffer)
 20        CONTINUE
 102       format('',f5.2)
 105       format('',1pe6.0)
        ENDIF
c
------------------------------------------------------------------------
        DO 10 j=1,53
          DO 10 k=1,53
            IF(ishp(j,k).EQ.0) GO TO 10
            IF(ishp(j,k).EQ.1) hh=h(j,k)
            IF(ishp(j,k).EQ.2) hh=hch(j,k)
            IF(hh.LT.rdep(1))                        icolor=idepcol(1)
            IF(hh.GE.rdep(1).AND.hh.LT.rdep(2)) icolor=idepcol(2)
            IF(hh.GE.rdep(2).AND.hh.LT.rdep(3)) icolor=idepcol(3)
            IF(hh.GE.rdep(3).AND.hh.LT.rdep(4)) icolor=idepcol(4)
```

```fortran
      IF(hh.GE.rdep(4).AND.hh.LT.rdep(5)) icolor=idepcol(5)
      IF(hh.GE.rdep(5).AND.hh.LT.rdep(6)) icolor=idepcol(6)
      IF(hh.GE.rdep(6).AND.hh.LT.rdep(7)) icolor=idepcol(7)
      IF(hh.GE.rdep(7).AND.hh.LT.rdep(8)) icolor=idepcol(8)
      IF(hh.GE.rdep(8).AND.hh.LT.rdep(9)) icolor=idepcol(9)
      IF(hh.GT.rdep(9))                   icolor=idepcol(10)
      dummy=setcolor(icolor)
      dummy=rectangle_w( $GFILLINTERIOR,2*(k+66),2*(j+6)
     +        ,2*(k+67),2*(j+7))
      IF(indexinf.EQ.0) GO TO 11
      vv=vinf(j,k)
      IF(vv.LT.rinfl(1))                   icolor=iinfcol(1)
      IF(vv.GE.rinfl(1).AND.vv.LT.rinfl(2)) icolor=iinfcol(2)
      IF(vv.GE.rinfl(2).AND.vv.LT.rinfl(3)) icolor=iinfcol(3)
      IF(vv.GE.rinfl(3).AND.vv.LT.rinfl(4)) icolor=iinfcol(4)
      IF(vv.GE.rinfl(4).AND.vv.LT.rinfl(5)) icolor=iinfcol(5)
      IF(vv.GE.rinfl(5).AND.vv.LT.rinfl(6)) icolor=iinfcol(6)
      IF(vv.GE.rinfl(6).AND.vv.LT.rinfl(7)) icolor=iinfcol(7)
      IF(vv.GE.rinfl(7).AND.vv.LT.rinfl(8)) icolor=iinfcol(8)
      IF(vv.GE.rinfl(9).AND.vv.LT.rinfl(9)) icolor=iinfcol(9)
      IF(vv.GT.rinfl(9))                   icolor=iinfcol(10)
      dummy=setcolor(icolor)
      dummy=rectangle_w( $GFILLINTERIOR,4.+k+1,65.*2+j+1
     +        ,4+k+2,65.*2+j+2)
c
11    IF(i.GT.nitrn+1) GO TO 10
      IF(irain.eq.0.AND.i.ne.1.AND.i.ne.nitrn+1) GO TO 10
      IF(irain.eq.1.AND.icall.eq.0) GO TO 10
      rr=rint(j,k)*(100)*3600
      IF(rr.LT.rrain(1))                   icolor=irancol(1)
      IF(rr.GE.rrain(1).AND.rr.LT.rrain(2)) icolor=irancol(2)
      IF(rr.GE.rrain(2).AND.rr.LT.rrain(3)) icolor=irancol(3)
      IF(rr.GE.rrain(3).AND.rr.LT.rrain(4)) icolor=irancol(4)
      IF(rr.GE.rrain(4).AND.rr.LT.rrain(5)) icolor=irancol(5)
      IF(rr.GE.rrain(5).AND.rr.LT.rrain(6)) icolor=irancol(6)
      IF(rr.GE.rrain(6).AND.rr.LT.rrain(7)) icolor=irancol(7)
      IF(rr.GE.rrain(7).AND.rr.LT.rrain(8)) icolor=irancol(8)
      IF(rr.GE.rrain(8).AND.rr.LT.rrain(9)) icolor=irancol(9)
      IF(rr.GT.rrain(9))                   icolor=irancol(10)
      dummy=setcolor(icolor)
      dummy=rectangle_w( $GFILLINTERIOR,2*(k+3),2*(j+6)
     +        ,2*(k+4),2*(j+7))
10    CONTINUE
c     ------------------------------------------------------------
      dummy=setcolor(0)
      dummy=rectangle_w( $GFILLINTERIOR,114.*2,63.*2,124.*2,71.*2)
      dummy=setfont('t''modern''h12w8b')
      dummy=setcolor(11)
      call moveto_w(2.*115.,2.*64.,wxy)
      write(buffer,122) i*dt/60.
      call outgtext(buffer)
      call moveto_w(2.*115.,2.*67.,wxy)
      write(buffer,122) qout
      call outgtext(buffer)
122   format(f6.1)
```

65

```fortran
      xx = 1.*(i-nplt) / (1.*niter)
      if((i-nplt).lt.0) xx=0.
      xx = xx * 88.
      xx = xx + 36.
      yy = qold / qmax
      yy = yy * 28.
      yy = 92. - yy
      call moveto_w(2*xx,2*yy,wxy)
      xx = 1.*i / (1.*niter)
      xx = xx * 88.
      xx = xx + 36.
      yy = qout / qmax
      yy = yy * 28.
      yy = 92. - yy
      dummy=setcolor(12)
      dummy=lineto_w(2*xx,2*yy)
      RETURN
      END
C     ===============================
C     SET UP FONTS FOR GRAPHICS MODE
C     ===============================
      SUBROUTINE FONTS()
$NOLIST
      INCLUDE 'FGRAPH.FD'
$LIST
      INTEGER*2 IDUM2
      IDUM2=REGISTERFONTS('E:\MSLANG\LIB\*.FON')
      IDUM2=SETFONT('t''roman''h12w12b')
      RETURN
      END
```