DISSERTATION

TWO - DIMENSIONAL SUBSURFACE FLOW MODELING FOR WATERSHEDS UNDER SPATIALLY AND TEMPORALLY VARIABLE RAINFALL

Submitted by

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WE HEREBY RECOMMEND THAT THE DISSERTATION PREPARED UNDER OUR SUPERVISION BY AMIT SHARMA ENTITLED TWO DIMENSIONAL SUBSURFACE FLOW MODELING FOR WATERSHEDS UNDER SPATIALLY AND TEMPORALLY VARIABLE RAINFALL BE ACCEPTED AS FULFILLING IN PART REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY.

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ABSTRACT OF DISSERTATION

Two – dimensional subsurface flow modeling for watersheds under spatially and temporally variable rainfall

Subsurface flow constitutes an important part of the hydrologic cycle; it becomes especially important for land surfaces where most of the rain water infiltrates into the soil. Subsurface flow supplies water to the channels, or to the aquifer. In pervious soils, where the horizontal conductivity far exceeds the vertical conductivity, subsurface flow becomes the dominant process in the rainfall-runoff relationship of natural watersheds.

A two-dimensional finite difference scheme has been formulated to simulate subsurface flow within the surface runoff model CASC2D. The subsurface flow formulation is based on Darcy's law, assuming that the vertical permeability is negligible. The subsurface flow is calculated for each square grid cell that represents

spatially variable watershed characteristics. The physical properties, including surface roughness, soil infiltration parameters, hydraulic conductivity, and soil moisture, are assumed uniform within each grid cell.

The modified model CASC2DSUB is subsequently integrated with the Geographical Information system(GIS) application Geographical Resource Analysis Support System(GRASS4.1) incorporating, two-dimensional graphic capabilities, allowing continuous observation of the ongoing hydrological processes resulting from a rainfall-runoff event as simulation progresses.

The program is first tested on a virtual test plot under varying conditions of soil types, hydraulic conductivities, and uniform rainfall intensity (1.0E-5m/s). The results obtained for clayey soils, with low hydraulic conductivity (8.33E-7m/s), show that overland flow is the dominant process. For gravelly soils, with high hydraulic conductivity (3.0E-2m/s), all the water infiltrates into the ground, and subsurface flow is the dominant process. For sandy soils (K= 3.27E-5m/s), all the water infiltrates into the ground, but the subsurface flow drains the watershed slowly and most of the water is retained in the soil matrix.

The model applicability has been tested on the Goodwin Creek watershed in Mississippi. The model is calibrated using the rainstorm event of October 17, 1981, and verified with the rainstorm event on December 2, 1983. In each case, the simulated hydrograph replicated the observed hydrograph. Finally, the range of

rainfall intensities and soil types for which surface or subsurface flow is predominant is defined. It is observed that for the permeable sandy soils, with hydraulic conductivities ranging from 1.0E-5m/s to 1.0E-3m/s under rainfall intensities less than 1 in/hr(7.055E-06m/s), the response of a watershed in terms of rainfall runoff would mostly be influenced by subsurface flow. For clayey soils with hydraulic conductivities ranging from 1.0E-8m/s to 1.0E-7m/s, and rainfall intensities in excess of 0.1 in/hr(7.055E-07m/s), the response of the watershed would be governed by surface flow.

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DEDICATION

To,
My Father and Mother …….

TABLE OF CONTENTS

TABLE OF CONTENTS

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF FIGURES

LIST OF TABLES

CHAPTER I

INTRODUCTION

The hydrologic cycle is a continuous process in which water evaporating from the oceans moves inland and produces precipitation. The precipitation, once on the ground, gets dispersed in various pathways. Some of the precipitation is retained by the vegetation (interception), and may return to the atmosphere by evapo-transpiration. A portion of the precipitated water gets distributed as overland flow or direct runoff, culminating into streams. Some of the rainfall infiltrates the soil system, and in the subsurface environment gets referred to as interflow or subsurface flow. Some portion of infiltrated water percolates deep down and joins the groundwater system as groundwater flow. Finally, all these portions flow to lower elevations and discharge into the ocean, thus completing the hydrologic cycle.

The study and understanding of the factors affecting the various basin flow processes is still one of the key areas of research in hydrology. The major factors that may affect the rainfall-runoff transformation process and their interaction at a basin scale includes the spatial and temporal distribution of precipitation, topography, evapotranspiration, drainage network morphology, heterogeneity of soil characteristics, bedrock lithology, vegetation cover and land use practices. These factors influence the magnitude and distribution of the various runoff processes, such as surface runoff and subsurface runoff, along with storage in the porous medium of the soil matrix.

Depending upon the characteristics of a basin and the prevailing climatic conditions, certain flow generating mechanisms will be dominant within a given watershed. Dunne (1978) summarized the physioclimatic controls on three mechanisms of storm flow generation on catchments --- infiltration excess, saturation excess, and subsurface storm flow. He stated that the infiltration excess runoff is generated from partial areas where surface hydraulic conductivities are low, while the saturation excess runoff is generated in areas with shallow water tables and wetlands. The subsurface may form an important part of the hydrologic cycle, especially in areas where most of the water infiltrates into the soil. The subsurface flow is likely to be active and dominant on steep, humid forested hillslopes with very permeable surface soils. As a result, the overland flow generated contributes very little, if at all, towards hydrograph generation. The major portion of water is in the subsurface, and drains into the channels, and flows out of the watershed outlet. Hence the contribution towards hydrograph generation comes mostly from subsurface flow and not overland flow. In the realm of hydrology, overland flow has been widely modeled, as a rainfall- runoff process in determining the response of a watershed. In the research documented in this dissertation subsurface flow is modeled as the dominating process contributing towards the watershed response, and the conditions are determined under which the influence of the subsurface is more forthcoming.

1.1. PRIMARY OBJECTIVE SPECIFICATION

The main objectives governing the research may be summed up as follows:

- Modify the code CASC2D to incorporate subsurface flow.
- Determination of spatial and temporal rainfall effects on subsurface flow, using the Goodwin Creek field data.
- Determination of the conditions (such as rainfall intensity, hydraulic conductivity, etc.) for which subsurface flow is dominant compared to surface flow in predicting watershed response.

1.2. APPROACH

To achieve the designated goals, the existing rainfall-runoff model CASC2D was selected to calculate surface runoff from spatially and temporally distributed precipitation. Subsequently a subsurface program was developed and linked to CASC2D. The subsurface component was calibrated, and simulations were run on a test watershed with different soil types. The Goodwin Creek watershed in Mississippi was selected for the simulation of the CASC2DSUB(a cascade program for calculation of subsurface flow) program on actual field data. Finally, dimensional analysis was used to quantify the conditions under which subsurface flow is the dominant physical process contributing to the watershed response. The following steps describe the approach that will be followed in this research:

- Formulation of temporal and spatial varying physically-based 2D subsurface scheme.
- Test the modified code on an example watershed.
- Calibration and validation of the developed code.
- Implementation of the modified CASC2D on the Goodwin Creek watershed.
- Determination of spatial and temporal rainfall effects on subsurface flow, using Goodwin Creek watershed data.
- Development of graphical capabilities to view temporal and spatial variations of surface flow, subsurface flow, and the channel flow.
- Dimensional subsurface flow analysis.

The dissertation format is designed as follows: Chapter II reviews the most pertinent literature related to the subsurface modeling. It also reviews the components of the model CASC2D. Chapter III presents the theoretical overview of the model CASC2DSUB. It discusses the application of CASC2DSUB on a virtual watershed, and the results obtained for different soil types. Chapter IV discusses the calibration and verification of the model CASC2DSUB on the Goodwin Creek watershed in Mississippi. Chapter V presents the analysis of subsurface flow and determines the conditions under which subsurface flow affects the watershed response. Chapter VI presents the summary and conclusions of this study. Appendix A presents the source code for the model CASC2DSUB. Appendix B lists programs used for the graphic visualization in GRASS4.1. Samples of input data files, topographic elevation files, and rainfall intensity files are given in Appendix C. The files showing the water depth matrices for each of the physical process for the virtual watershed are displayed in Appendix D.

CHAPTER II

LITERATURE REVIEW

The concept of subsurface storm flow is not new. Its importance in contributing to the flood hydrograph has been recognized as far back as the 1930's (Hurush 1936; Hurush and Brater 1941). However, the popularity of Hortonian overland flow (Horton 1933, 1945) due to infiltration excess has dominated the rainfall-runoff research, and the subsurface flow has been neglected in most runoff studies. This surface runoff mechanism is known to occur in semi-arid regions and agricultural lands, such as in the mid-western United States (Dunne et al. 1975), where the soil infiltration capacities are usually less than rainfall intensities. Betson (1964) brought out the inadequacies in Horton's model. His main point was that the 'Hortonian' overland flow was rarely widespread throughout the draining catchment. Consequently, the production of infiltration excess overland flow would occur only on some parts of the watershed. This phenomena became known as the "partial-area concept", and is likely to be found in disturbed or poorly vegetated areas in sub-humid and semi-arid regions (Wolock 1993).

In humid regions, where the infiltration capacity of undisturbed forest soil is high, Hortonian overland flow is unlikely to occur. Instead, subsurface flow is the major stream flow-generating mechanism (Dunne and Black 1970;Dunne et al. 1975). Subsurface storm flow is predominant where the near surface soil layer has very high lateral transmissivity and the hill slopes are steep (Hewlett and Hibbert 1967). Hence the subsurface runoff can be a major contributor to the flood hydrograph in the regions with slopes having permeable soils, which decrease in permeability with depth or which overlie an impermeable bedrock. This gives rise to the variable-source (contributing) area (VSA) concept. According to the VSA concept, the stream flow is generated during precipitation events on saturated soil surfaces called 'source areas', which occur in locations where the water table rises to the land surface. Hence the source areas for subsurface storm flow generation are generally found in different locations than the source areas generating infiltration excess overland flow.

Thus, for many humid, forested watersheds, near-subsurface storm flow (Whipkey 1965) is a major contributor to the response hydrograph during a rainfall event. In the literature, the rapid subsurface response has been synonymously referred to as interflow (Beven 1989), saturated interflow and through flow (Kirby and Chorley 1967). Various theoretical speculations have been attributed to the subsurface phenomenon. Macropores and preferential flow mechanisms were put forward by Whipkey (1965); Mosley (1979); and Beven and Germann (1982).

Hewlett and Hibbert (1967) suggest the displacement response of the saturated surface moisture, termed as translatory flow to be the responsible mechanism. In 1991 McCord et al. showed that the preferential lateral down-slope near-surface flow may be induced by the effect of state dependence anisotropy in hydraulic conductivity. As a result, the simulation of near-surface stormflow for humid, forested watersheds, is crucial for a rainfall-runoff model to generate satisfactory and physically realistic results.

Mathematical models of subsurface flow have been in use since the late 1800's (Dooge 1957,1973; Amorocho and Hart 1964; Freeze and Harlan 1969; and Todini 1989). To deal with more realistic and complex situations, numerical solutions became the preferred mode of model application. Since 1960, numerical models have been widely used to study hydrological phenomena.

The effort has been to understand the physics that governs the transformation of rainfall into runoff (Dunne 1978; Freeze 1980). Rainfall acts as the input to the rainfall-runoff process, which gets distributed into various components of evaporation, infiltration, depression storage, overland flow, subsurface flow, groundwater flow, and finally channel flow. The response of a watershed is highly governed by rainfall intensity, duration, land use, soil type, channel type, shape of the watershed, slope, and other physiographic features (Biedent and Huber 1988). Hydrologic simulation models can be classified based on the variety of characteristics. For watershed analysis, the categories of interest include lumped parameter models (Snyder Unit Hydrograph; Snyder 1938) versus distributed parameter models with representation of various processes based on the conservation of mass, energy, and momentum (Bathurst 1986, Bathurst and Cooley 1996; Abbott et al., 1986a,b; Beven et al., 1987; Binely et al., 1989). Event based models include HEC-1 (Hydrologic Engineering Center,1975,1979,1980,1981), SWMM (EPA Storm Water Management Model; Metcalf & Eddy Inc.,1971, Huber et. al., 1981), and SCS TR20 (Soil Conservation Service, 1975a). Continuous models include the Stanford Watershed Model (Crawford and Linsley 1966), SWMM, HSPF (Hydrologic Simulation Program FORTRAN, Hydrologic Eng. Center; 1980), STORM (Storage, Treatment, Overflow, Runoff Model, HEC, 1975; Roesner et al., 1974), and the stochastic models versus deterministic models. Since the present research concerns event based modeling, the discussion here is limited to event-based models (i.e., lumped, distributed and semi distributed models) in general. Event models are short-term, designed for simulation of individual rainfall-runoff events. The objective relates to the evaluation of direct runoff. These models are therefore popularly applied for evaluation of flood flows.

HEC-1, or the "Flood Hydrograph Package" was developed by the Hydrologic Engineering Center (HEC) in 1981 and updated in 1985. It is designed for the simulation of flood events in watersheds and river basins. HEC-1 is an event based model with simulations limited to a single storm event. For rainfall-runoff simulation, the processes considered are precipitation, interception/infiltration, subbasin runoff, base flow, and flood hydrograph routing through stream channels or reservoirs.

Technical Release No.20: "Computer program for Project Formulation - Hydrology", or TR-20, was developed by the USDA Soil Conservation Service in cooperation with the Hydrology laboratory, Agricultural Research Service. The original version was released in 1965, but the current version was released in 1983. This model is also used for the evaluation of flood events. It computes direct runoff from any rainstorm, develops flood hydrographs from surface runoff, and routes flow through the channels. It combines the routed hydrograph with those from the tributaries, and computes the peak discharges, their times of occurrence, and the water surface elevations at any cross section. It is used in watersheds where peak discharges are due to thunderstorms or other high intensity, short duration storms.

The Stormwater Management Model (SWMM), was developed in 1970 by Metcalf and Eddy, Inc., the University of Florida, and Water Resources Engineers, Inc., in conjunction with the U.S Environmental Protection Agency. SWMM models urban stormwater runoff and combined sewer overflow. It is an urban runoff model that simulates both the continuous, as well as specific rainfall event for different watersheds. The model simulates storm events based on the rainfall inputs and the system characteristics (catchment soil, catchment topography, storage treatment, and receiving water) and predicts water quantity and quality values.

The Stanford Watershed Model (SWM) IV (Crawford and Linsley 1966) was developed at Stanford University in the early sixties. It is a conceptual, lumped-parameter, continuous process model that is used for the simulation of hourly or daily streamflows at the watershed outlet. The interflow is conceptualized as (i) detention of moisture into the interflow store based on empirical parameters, and (ii) the drainage of the detained interflow using a simple linear storage model, where the linear constant is estimated from hydrograph analysis. The model requires a large amount of input data for a watershed, and is therefore not very commonly used. Kubota and Sivapalan (1995) used SWM to develop a macroscale model of subsurface stormflow generation on a steep forested catchment in Japan where the volume of saturated groundwater is related to the discharge (a simple storage function), as well as to the areal extent of surface and subsurface saturated areas.

In Europe the model "SHE" (System Hydrologique Europeen) has been quite popular among hydrologic modelers. The SHE model (Abbott et al., 1986a,b) was jointly developed by the Danish Hydraulic Institute, the Institute of Hydrology (UK), and the French consulting company SOGREAH. The model integrates the partial differential equations expressing the continuity of mass and momentum and energy conservation, or by empirical equations derived from independent experimental research. Previous physically-based models mostly produced rainfall-surface runoff processes, and were relevant to small urban catchments (Wooding 1965-1966), or small mountain catchments (Freeze and Witherspoon 1967- 1968). The hydrological components modeled are snowmelt, canopy, interception, evapotranspiration, overland and channel flow, and unsaturated and saturated subsurface flow. The models not only determine the flow at the outlet at each time step, but the distribution and magnitude of all other basin responses and processes can be simulated spatially according to the grid size used to represent the basin. The large amount of data required for this type of model operation could render some constraints, as all the data may not be available, causing uncertainties in the values of catchment parameters, which in turn may lead to uncertainties in prediction. However, the SHE model compensates for these types of errors by quantifying the uncertainties through sensitivity analyses, and acts as a good decision support system.

TOPMODEL (Beven and Kirkby 1979; Beven and Wood 1983; Beven 1989) is a topography-driven semi-distributed hydrological model that embraces principally the variable source area concept, although simulation of infiltration excess overland flow is also incorporated in some versions of TOPMODEL (Wood et al., 1990). The model predicts the total streamflow, and the overland and subsurface flow components, and can perform the mapping of the depth to the water table. The model has been successfully applied to many catchments in humid, temperate regions where the water table is shallow and the terrain has moderate to steep slopes. In these regions, TOPMODEL works effectively as the assumptions such as effective hydraulic gradient approximated by the local terrain slope and soil exhibiting a negative exponential decay of the hydraulic conductivity are well met. However, for some drier regions such as the Booru-Borotou catchment in the Cote d'Ivoire (Quinn and Beven 1993), the results suggest that the TOPMODEL will perform satisfactorily only when the catchment has "wetted up." In other instances, for catchments where infiltration excess runoff mechanism is thought to be important, TOPMODEL failed to provide a satisfactory simulation since this mechanism is crudely simulated or ignored in the model. The above cases suggest that the model is somewhat restricted by its specificity to circumstances that agree with its assumptions, in particular, the exponential groundwater storage response and the dominance of the variable source area runoff mechanism for wet watersheds. This illustrates the restrictions on the geographical and climatic scope of TOPMODEL applications, as also suggested by Beven et al (1995).

2.1 CASC2D MODEL DESCRIPTION

Computer modeling of physical hydrological processes (i.e., rainfall-runoff, and subflow processes in the case of CASC2D) governing the response of a watershed to rainfall, are based on the solution of partial differential equations. These have been numerically solved to simulate rainfall-runoff, and subflow events. Based on the Green-Ampt infiltration scheme, the surface runoff is separated and is modeled as two-dimensional finite difference explicit overland flow, and one-dimensional channel flow.

The model CASC2D is a physically based two dimensional computer model that can be used to determine the runoff hydrograph generated from any temporally and spatially varied rainfall event. The model was developed at Colorado State University by Julien and Saghafian (1991) and includes Green and Ampt (1911) infiltration calculation and diffusive wave channel routing routines. CASC2D uses a diffusion wave approximation to the de St.-Venant equations of continuity and momentum to formulate the overland as well as the channel flow. The diffusive wave scheme is selected over the kinematic wave for it's representation of stored water and it's application in regions of small slope and/or high roughness.

2.2 THEORY AND FORMULATION

The original CASC2D was purely an event-based model, but the modified CASC2D called CASCSUB2D, although event-based, contains encompassed features of a continuous process model with the addition of subsurface flow.

2.3 PROCESSES AND THEIR GOVERNING EQUATIONS

2.3.1 Precipitation

The model is flexible in that it allows either a uniform rainfall intensity discerned by the user or it interpolates the spatially variable rainfall over the watershed, based on an inverse distance squared scheme, when rainfall intensities are recorded at various raingage locations. The equation may be represented as:

$$i^{t}(j,k)=\frac{\sum_{m=1}^{NRG}\frac{i_{m}^{t}(jrg,krg)}{d_{m}^{2}}}{\sum_{m=1}^{NRG}\frac{1}{d_{m}^{2}}} \qquad (2.1)$$

where:

$i^t(j,k)$ = rainfall intensity in element (j,k) at time t (m/s).

$i^t_m(jrg,krg)$ = rainfall intensity recorded at the m^th^ rainfall gage located at point (jrg,krg) (m).

d_m = distance between element (j,k) and m^th^ raingage at location (jrg,krg) (m).

NRG = total number of rainfall gages.

2.3.2 Infiltration

Infiltration is best defined as the movement of water through the soil surface into the soil. Infiltration from rainfall usually occurs with very shallow depths of water on the surface of the soil. The quantity of the infiltrated water is generally on the order of a few inches per day and does not saturate great depths of soil. Thus the infiltrated water is not a great contributor to the groundwater unless the soil is highly permeable.

Simulation of a rainfall-runoff event on a watershed requires determination of excess rainfall-producing overland flow. This is achieved by deducting the infiltrated portion from the incurring rainfall. The parameters of the Green-Ampt equation are based on physical characteristics of the soil, hence can be obtained from field measurements or laboratory experiments. The infiltration process is formulated on the basis of Green-Ampt infiltration equation as (Philip, 1983):

$$f = K_s \left(1 + \frac{H_f M_d}{F} \right) \tag{2.2}$$

where
f = infiltration rate; (L/T)
K_s = hydraulic conductivity at normal saturation ; (L/T)
H_f = capillary pressure head at the wetting front ; (L)
M_d = soil moisture deficit equal to $(\theta_c - \theta_i)$; (dimensionless)
θ_c = effective porosity equal to $(\phi - \theta)$; (dimensionless)
ϕ = total soil porosity; (dimensionless)
θ_r = residual saturation: (dimensionless)
θ_i = soil initial moisture content; (dimensionless)
F = total infiltrated depth; (L)

The finite difference scheme for the Green-Ampt equation can be formulated as follows:

$$f^{t+\Delta t} = K_s \left[1 + \frac{H_f M_d}{F^t + \Delta \frac{t}{2} f^{t-\Delta t}} \right] \tag{2.3}$$

Infiltration rate for the new time step $t+\Delta t$ is obtained by solving the above equation (2.3). Selection of the Green-Ampt equation for the infiltration is based on the criteria that its, parameters are dependent on the physical characteristics of the soil, and therefore can be easily measured from the actual field conditions. Since the soil parameters are not derived from lab experiments, they tend to simulate the natural process of infiltration rather accurately, also it compares extremely well with the Richards equation (Saghafian, 1992).

2.3.3 Overland flow routing

If the rainfall rate over the watershed is less than the rate of infiltration and the soil is dry, then the direct runoff from the surface, or the overland flow, will be zero. On the other hand, once infiltration is accounted for, that is once the soil is saturated with water and the rainfall rate is much greater than the infiltration rate, then the excess rainfall accumulates as surface water and begins to flow, giving rise to overland flow. The overland flow is the surface runoff that occurs in the form of sheet and rill flow on the land surface without particular preference to channel delineation. Horton (1933) proposed that overland flow is common and areally widespread. Later, Betson (1964) stated that the overland flow problem can be solved through: storage concept; kinematic wave technique; diffusion wave technique; and dynamic wave technique. In general the kinematic wave formulation has been largely followed, but this formulation cannot predict backwater effects due to downstream disturbances in a channel, which is important during flood simulation. Hence, this phenomenon is modeled by the diffusive wave finite difference approximation of the St.-Venant equations of continuity and momentum. The explicit formulation is selected based on the ease of running the model, requires no internal boundaries, and is probably best for small watersheds.

The 2D continuity equation in Partial Differential Equation (PDE) form is given as:

$$\frac{\partial h}{\partial t}+\frac{\partial q_x}{\partial x}+\frac{\partial q_y}{\partial y}=\bar{e} \qquad (2.4)$$

where

h = surface flow depth

q_x = unit flow rate in x-direction

q_y = unit flow rate in y-direction

$\bar{e}$ = excess rainfall equal to (i-f)

i = rainfall intensity

f = infiltration rate

x,y = cartesian spatial coordinates

t = time

The 2D formulation of the momentum equations may be stated as:

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = g\left(S_{ox} - S_{fx} - \frac{\partial h}{\partial x}\right) \quad \text{-- } x \text{ direction} \qquad (2.5)$$

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} = g\left(S_{oy} - S_{fy} - \frac{\partial h}{\partial y}\right) \quad \text{-- } y \text{ direction} \qquad (2.6)$$

where: u,v = average velocities in the x and y directions
S_{ox}, S_{oy} = bed slopes in x and y directions
S_{fx}, S_{fy} = friction slopes in x and y directions
g = acceleration due to gravity
h = water depth

The left-hand side of equations (2.5) and (2.6) represents the local and convective acceleration terms, while the right-hand side represents the net forces along the x and y directions. Hence, the momentum equations are expressed by equating the net forces per unit mass in each direction to the acceleration of flow in the same direction.

Assuming steady flow, the momentum equation for diffusive wave formulation may be expressed as:

$$S_{fx} = S_{ox} - \frac{\partial h}{\partial x} \tag{2.7}$$

A resistance law needs to be established to relate flow rate to depth and other parameters. This is required, because the three equations of continuity and momentum (equations 2.4, 2.5, and 2.6) contain five unknown hydraulic variables, and another equation is needed to solve for the variables.

In the case of turbulent flow, the Manning's empirical resistance equation may be selected for the depth-discharge relationship. This is be expressed as:

$$q = \frac{S_f^{1/2}}{n} h^{5/3} \tag{2.8}$$

where $\alpha = \frac{S_f^{1/2}}{n}$; $\beta = 5/3$; n = Manning's roughness coefficient.

The overland flow is routed based on the conservation of mass and momentum. The continuity equations are formulated based on a first-order finite difference explicit scheme. For example, the formulation for an element (j,k) would be:

$$h^{t+\Delta t}(j,k) = h^t(j,k) + \bar{e}\Delta t - [\frac{q_x^t(k \rightarrow k+1) - q_x^t(k-1 \rightarrow k)}{w}]\Delta t - [\frac{q_y^t(j \rightarrow j+1) - q_y^t(j-1 \rightarrow j)}{w}]\Delta t \tag{2.9}$$

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

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^t_x (k→k+1), q^t_x (k-1→k) = unit flow rates in the x-direction at time t, between the elements (j,k) and (j,k+1), and (j,k-1) and (j,k) respectively.

q^t_y (j→j+1), q^t_y (j-1→j) = unit flow rates in the y-direction at time t, between the elements (j,k) and (j+1,k), and (j-1,k) and (j,k) respectively.

w = square element size.

Now the whole watershed is discretized into grid elements, and the flow at each time step is determined from element (j,k) to element (j, k+1), or vice versa ,and from element (j,k) to (j+1, k), or vice versa. The direction of flow is based on the sign of the friction slope, which as a diffusive wave formulation in the x and y directions may be expressed as:

$$S_{fx}^{t}(k-1\rightarrow k)=S_{ox}(k-1\rightarrow k)-\frac{h^{t}(j,k)-h^{t}(j,k-1)}{W} \qquad (2.10)$$

$$S_{fy}^{t}(j-1\rightarrow j)=S_{oy}(j-1\rightarrow j)-\frac{h^{t}(j,k)-h^{t}(j-1,k)}{W} \qquad (2.11)$$

The bed slopes are calculated based on the topographical elevations (E) of each grid cell. The bed slopes in the x and y direction may be expressed as:

$$S_{ox}(k-1\rightarrow k)=\frac{E(j,k)-E(j,k-1)}{W} \qquad (2.12)$$

$$S_{oy}(j-1 \rightarrow j) = \frac{E(j,k) - E(j-1,k)}{W} \tag{2.13}$$

Once the fluid flow direction has been determined based on the friction slope and the assumption of turbulent flow is conceived, then, the unit flow discharge from one cell to another may be expressed as:

$$q_x{}'(k-1 \rightarrow k) = \frac{1}{n(j,k-1)}\left[h'(j,k-1)\right]^{5/3} * \left[S_{fx}{}'(k-1 \rightarrow k)\right]^{1/2} \; if\, S_{fx}{}'(k-1 \rightarrow k) \geq 0 \tag{2.14}$$

$$q_x{}'(k-1 \rightarrow k) = -\frac{1}{n(j,k)}\left[h'(j,k)\right]^{5/3} * \left[-S_{fx}{}'(k-1 \rightarrow k)\right]^{1/2} \; if\, S_{fx}{}'(k-1 \rightarrow k) < 0 \tag{2.15}$$

The above equations represent unit discharge in the x-direction. The representations in the y-direction are also done in a similar manner, that is from cell (j,k) to (j+1,k).

2.3.4 Channel flow routing

The program has been modified such that it allows flexibility of usage. The modeler can run the program without any channels on the watershed or run it with the inclusion of the channel network by specifying the index status in the input data file. The index status is the switch defined in the input data file, where "0" is indicative of no channel network, while "1" is indicative of the channel network. The channel network is defined as a series of cell elements symbolized by the numeral 2. During the simulation of a rainfall-runoff event the overland runoff on reaching the channel element discharges into the channel element and gets routed as a one-dimensional diffusive wave approximation of the de St.-Venant equations.

Channel flow formulation based on the 1D diffusive wave conservation of mass equation, also called the continuity equation may be represented as:

$$\frac{\partial A}{\partial t}+\frac{\partial Q}{\partial x}=q_l \qquad (2.16)$$

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

The equation states that the change in flow per unit length (in the flow direction) in a control volume is balanced by the change in flow area per unit time.

The resistance to the flow is formulated by the Manning's equation, and the discharge rates assuming turbulent flow may be represented as:

$$Q=\frac{1}{n} A\, R^{2/3} S_f^{1/2} \qquad (2.17)$$

where:
R = hydraulic radius
S_f = friction slope
n = resistance coefficient

2.4 VISUALIZATION CAPABILITY - GIS INTEGRATION

The Geographical Information System (GIS) GRASS 4.1 is used in conjunction with the Fortran code of the modified CASC2D model to develop the visual capabilities. GRASS4.1 was developed at USACERL (U.S. Army Construction Engineering Research Laboratories) in Champaign, Illinois. The

GRASS GIS can handle both raster (grid-based) files as well as the vector (line-based) files. The popularity of GIS based or linked models has increased considerably as the availability of data such as elevation grids, land use grids has increased. Chansheng et al. (1993) integrated GIS with a computer model to evaluate the impacts of agricultural runoff on water quality. Tchikawa et al. (1994) developed a basin geographic information system using TIN-DEM structure. Nelson (1994) worked on the development of a watershed modeling system that imported both raster and vector data for use in different hydrologic models.

In summation, it can be said that although the concept of subsurface flow is not new, the research in this area has been rather constrained. The literature reviewed includes some of the models incorporating subsurface flow processes, such as interflow and ground water flow. CASC2D, primarily a single rainstorm event-based overland flow model has been reviewed in detail as it forms the surface flow block to which the subset subsurface flow has been added to study the response of a watershed. In addition the visual presentation of the ongoing physical processes due to the rainstorm event is displayed in GRASS4.1.

CHAPTER III

PROPOSED TWO DIMENSIONAL SUBSURFACE FLOW MODEL

3.1 CONCEPT

Water received as a result of a rainfall storm event on a watershed, will either generate overland flow or subsurface flow depending on the soil types. If the watershed soils have high hydraulic conductivity, then most of the water will infiltrate to the subsurface. Once the water is in the subsurface, it travels laterally and meets the channel and is routed as channel flow, finally going out of the watershed. There exist various methods by which a subsurface model could be formulated (such as physical lab models), but a numerical modeling approach was selected, on account of the ease of handling large data sets and being able to simulate various scenarios in a short period of time. An existing surface model CASC2D was selected, a program for the subsurface flow simulation was developed, and this program was linked to the surface model. Figure 3.1 depicts the regions and the physical processes during the rainfall-runoff phenomenon.

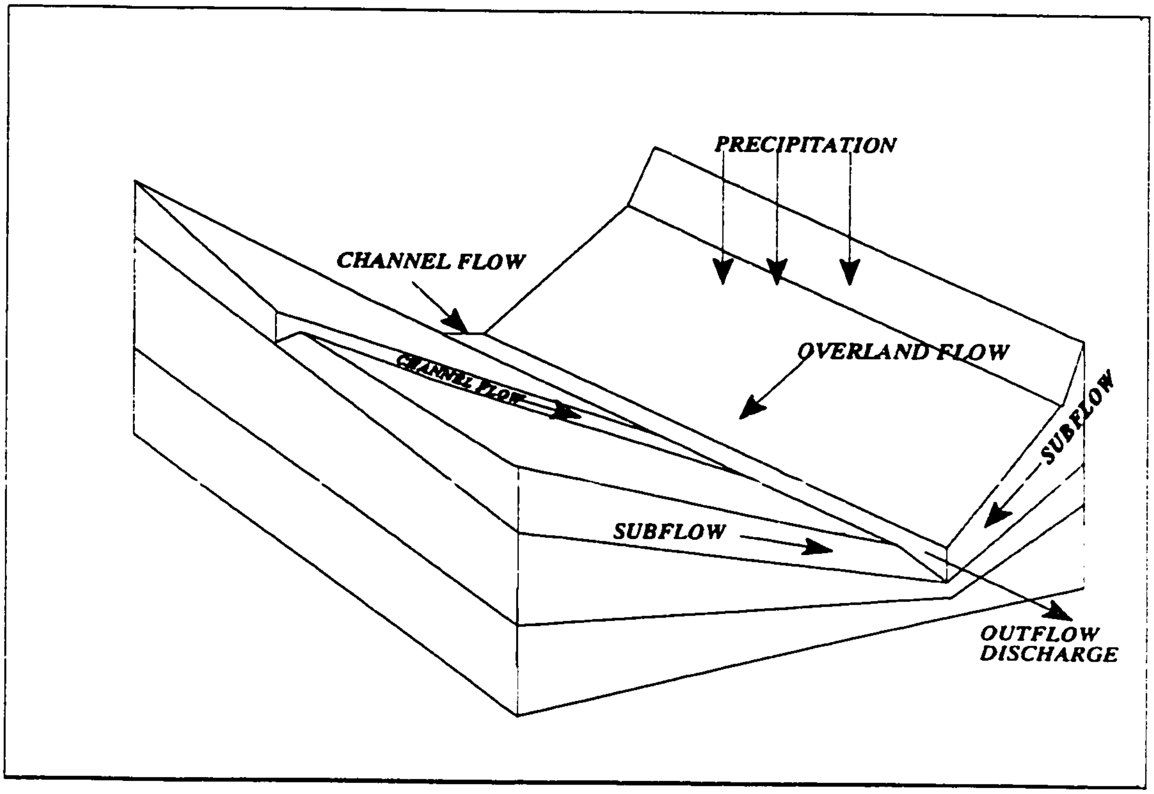


Figure 3.1: Schematic representation of various flow processes

3.2 MODEL ASSUMPTIONS

The reliability of predictions developed using a subsurface model depend on how accurately the model approximates the field situations. Simplifying assumptions have been made in order to construct the model because the field situations are too complex to be simulated exactly. Assumptions for the model may be summarized as follows:

- No water occupying the drainable pore space is lost to the process of evapotranspiration.
- The soil matrix or the saturated material is homogeneous, isotropic, and physically stable.

- The soil matrix is uniform, contains no macropores, or preferential path.
- Flow occurs only in the saturated layer.
- The water has constant values of surface tension, viscosity, and density throughout the entire flow system and during all times under consideration.
- The hydraulic conductivity of the upper soil horizon is high relative to the lower layers causing saturation at the base of the permeable horizon leading to lateral subsurface flow downslope. (Zaslavsky and Sinai, 1981; Burt and Butcher, 1986.)
- A horizontal relatively impermeable barrier exists at some depth below the soil surface. Such a barrier forms a boundary for the flow region.
- The rainwater on infiltration saturates the soil matrix.

3.2.1 Subsurface flow Model Limitations based on Darcy's Law

The model is not applicable to the conditions where Darcy's Law applicability is questionable (Swarzendruber 1962), such as:

- Extremely small groundwater velocities.

  (compact clays with small hydraulic gradients)
- Flow through fractured rock.
- Large cavities in karst limestone, lavatubes etc., as groundwater

velocities are too large to be valid.

- Places of large density variations.

  (Freshwater - Saltwater interface)

  (Multiple fluid phase - LNAPLE, DNAPLE

3.3 SUBSURFACE PHYSICAL PROCESS FORMULATION

The CASCSUB2D is developed as a distributed parameter hydrologic simulation model. The model subdivides the watershed into two parts:

1. Surface block, which includes overland flow and channel flow.
2. Subsurface block, which includes saturated subsurface flow.

These blocks are then further subdivided into units or cells, by the grid system overlaying the watershed. The basic guiding component of the model is the hydrologic component. This component is divided into different modules, and each module consists of governing subroutines. These subroutines in turn analyze and simulate one of the hydrological processes, such as overland flow, subsurface flow, etc.

The St.-Venant equations of continuity and momentum are used here to describe the mechanics of subsurface flow. The 2D continuity equation in partial differential form can be written as:

$$\frac{P\partial h_{sub}}{\partial t}+\frac{\partial q_{(sub)_x}}{\partial x}+\frac{\partial q_{(sub)_y}}{\partial y}=f \qquad (3.1)$$

where h_{sub} = subsurface flow depth

$q_{(sub)x}$ = subsurface unit flow rate in x-direction

$q_{(sub)y}$ = subsurface unit flow rate in y-direction

f = infiltration rate

x,y = cartesian spatial coordinates

P = porosity

t = time

The 2D momentum equations (2.5) and (2.6) described earlier in chapter 2 may be simplified using the kinematic wave approximation, whereby all the terms except the bed slope and the friction slope become negligible:

$$S_{(sub)f} = S_{(sub)o} \tag{3.2}$$

where $S_{(sub)f}$ = subsurface friction slope (L/L)

$S_{(sub)o}$ = subsurface bed slope (L/L)

The resistance law for the subsurface flow relates velocity or discharge to depth and may be formulated in accordance with a depth-discharge relationship. The mass flux governing the transport of water that flows through the saturated porous soil can be formulated in accordance with Darcy's Law. If h_{sub} is the thickness or the height of the concerned layer, then:

$$q_{(sub)_x} = -Kh_{(sub)} \frac{\partial h_{sub}}{\partial x} = -Kh_{(sub)} S_{(sub)ox} \tag{3.3}$$

where:

K = is the hydraulic conductivity (L/T)

$\partial h/\partial x = S_{(sub)ox}$ = subsurface slope in x-direction.

$h_{(sub)}$ = subsurface depth of flowing water or the hydraulic head;

Now relating equation (3.3) with the depth-discharge relationship gives:

$q_{(sub)} = \alpha h_{(sub)}^{\beta}$

$KS_{(sub)ox} = \alpha$ and $\beta = 1$. Therefore we have: $(KS_{(sub)ox})h_{(sub)}^{\beta}$. This compares well with the overland flow relationship where we have: $\alpha = S(l/2)/n$ and $\beta = 5/3$.

The surface and subsurface flow processes may be compared based on the governing equations describing each of the process as observed in Table 3.1.

Table 3.1: Comparison of surface and subsurface flow

	SURFACE	SUBSURFACE
Continuity Equation	$\frac{dh}{dt}+\frac{dq_x}{dx}+\frac{dq_y}{dy}=e$	$\frac{Pdh_{sub}}{dt}+\frac{dq_{(sub)x}}{dx}+\frac{dv_{(sub)v}}{dt}=f$
Momentum Equation	Diffusive Wave Formulat. $S_{fx} = S_{ox} - \frac{\partial h}{\partial x}$	Kinematic Wave Formul. $S_{(sub)f} = S_{(sub)o}$
Resistance Eq. in Overland	$q=\frac{1}{n}h^{2/3}S_f^{1/2}$	$q = KS_{(sub)ox}h^{1}_{sub}$
Resistance Eq. in Channel	$q=\frac{1}{n}AR^{5/3}S_f^{1/2}$	
Time to equilibrium	$t_e=\frac{n^{3/5}L^{3/5}}{i^{2/5}S_o^{3/10}}$	$t_e=\left(\frac{L}{KS_{(sub)o}}\right)^{1}$

3.4 Numerical scheme

A two dimensional explicit numerical solution has been used to simulate the subsurface flow. The watershed for which the response is being determined is considered as the solution domain. The watershed is then overlaid by a predetermined square grid of size *w*, which is designated in the input data file. The field parameters such as hydraulic conductivity, soil moisture content, and capillary pressure are considered uniform within the cell. However, they may vary from one cell to the other, leading to a distributed nature of the model. A 2D finite difference grid may be represented as shown in Figure 3.2

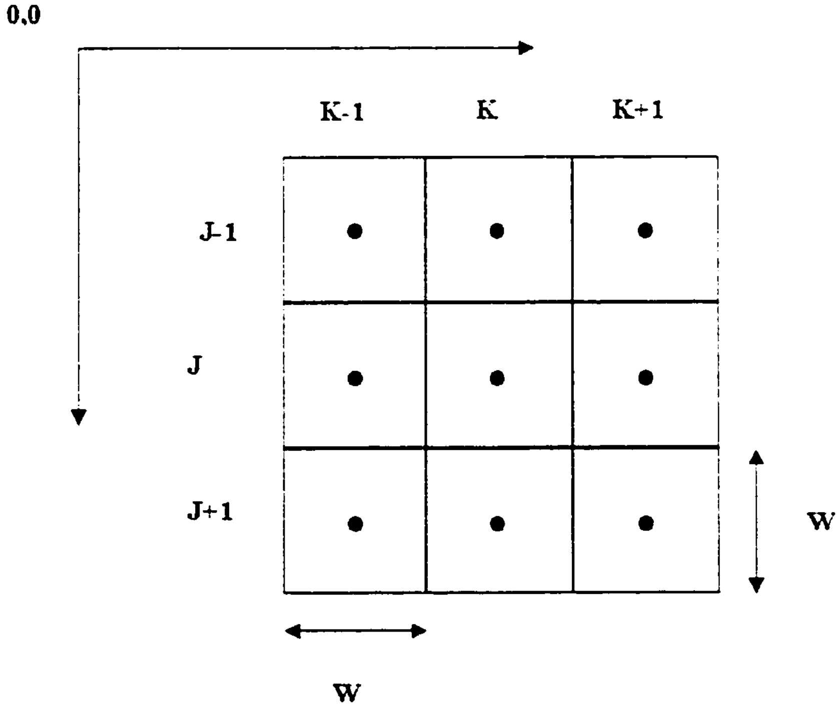

FINITE DIFFERENCE GRID REPRESENTATION

Figure 3.2 : Schematic representation of finite difference grid

The subsurface flow routing may be formulated as follows:

$$\frac{P\partial h_{sub}}{\partial t}+\frac{\partial q_{(sub)_x}}{\partial x}+\frac{\partial q_{(sub)_y}}{\partial y}=f \tag{3.4}$$

$$\frac{P\partial h_{sub}}{\partial t}=f-\frac{\partial q_{(sub)_x}}{\partial x}-\frac{\partial q_{(sub)_y}}{\partial y} \tag{3.5}$$

$$\partial h_{sub}=\frac{1}{P}[f\Delta t-\frac{\partial q_{(sub)_x}}{\partial x}\Delta t-\frac{\partial q_{(sub)_y}}{\partial y}\Delta t] \tag{3.6}$$

Since Δx and Δy =w: equation (3.6) can be written as:

$$\Delta h_{sub}=[f\Delta t-\frac{\Delta q_{(sub)_x}}{w}\Delta t-\frac{\Delta q_{(sub)_y}}{w}\Delta t]*\frac{1}{P} \tag{3.7}$$

now we can write $\Delta h_{(sub)} = h_{(sub)2}-h_{(sub)1} = h_{(sub)}^{(t+\Delta t)}-h_{(sub)}^{(t)}$; therefore equation (3.7) can be written as:

$$h_{sub}^{(t+\Delta t)}=h_{sub}^{(t)}+[f\Delta t-\frac{\Delta q_{(sub)_x}}{w}\Delta t-\frac{\Delta q_{(sub)_y}}{w}\Delta t]*\frac{1}{P} \tag{3.8}$$

According to the conservation of mass principle (continuity equation). the total mass (volume in this case) entering an element in a period of time is proportional to the change in mass (volume) within the same element over the same period of time. The first order approximation of equation (3.8) may be formulated as follows:

$$h_{sub}^{t+\Delta t}(j,k) = h_{sub}^{t}(j,k) + [f\Delta t - [\frac{q_{(sub)_x}^{\ t}(k \to k-1) - q_{(sub)_x}^{\ t}(k-1 \to k)}{w} - \frac{q_{(sub)_y}^{\ t}(j \to j-1) - q_{(sub)_y}^{\ t}(j-1 \to j)}{w}]\Delta t] * \frac{1}{P} \qquad (3.9$$

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

h_{sub}^{t} (j,k) = subsurface flow depth at element (j,k) at time t

Δt = time step duration

f = average infiltration rate over one time step beginning from time t

P = porosity

$q_{(sub)}{}^{t}{}_{x}$ (k→k+1), $q_{(sub)}{}^{t}{}_{x}$ (k-1→k) = subsurface unit flow rates in x-direction at time t, between the elements (j,k) and (j,k+1), and (j,k-1) and (j,k) respectively.

$q_{(sub)}{}^{t}{}_{y}$ (j→j+1), $q_{(sub)}{}^{t}{}_{y}$ (j-1→j) = subsurface unit flow rates in y-direction at time t, between the elements (j,k) and (j+1,k), and (j-1,k) and (j,k) respectively.

w = square element size.

The purpose of the subsurface program SUBFLO is to compute the subsurface flow (interflow) depth at the end of a given time step, and the subsurface discharge going to the channel at the down-stream end. The excitation to the system comes from the infiltrated depth, which is computed by subroutine INFILT (infiltration). The unit subflow rate in the SUBFLO program is calculated based on the flow direction, which is dependent on the sign of the friction slope (S_f). The kinematic wave approximation may be formulated as:

$$S_{(sub)f}(k-1 \to k) = S_{(sub)o}(k-1 \to k) \qquad (3.10)$$

$$S_{(sub)o}(k-1,k) = \frac{E(j,k-1) - E(j,k)}{w} \qquad (3.11)$$

where $S_{(sub)o}$ is the subsurface bed slope and E represents the ground surface elevation at the center of the square element. The discharge from one cell to another may be calculated using Darcy's law as:

$$q_{(sub)}{}^{t}_{x}(k-1 \rightarrow k) = K(j,k-1)\, h^{t}_{(sub)}(j,k-1)\, S^{t}_{(sub)fx}(k-1 \rightarrow k) \tag{3.12}$$

where $h^{t}_{(sub)}(j,k-1)$ is the bulk (that is, water plus the soil particles) divided by the porosity, so as to obtain only the water head.

Now the volume of water in each cell may be calculated as: $V=q*w*\Delta t$ and the height of water as: $h=V/w^2$ or $h=(q/w)\Delta t$

The flow chart (Fig 3.3) given on the next page is a schematic of how the complete program along with subsurface flow is designed. The flow chart (Fig.3.4) outlines only the subsurface flow routine SUBFLO. Once the computer program for subsurface flow was designed and linked to the surface component of the runoff, an example watershed was created to ascertain the validity of the model.

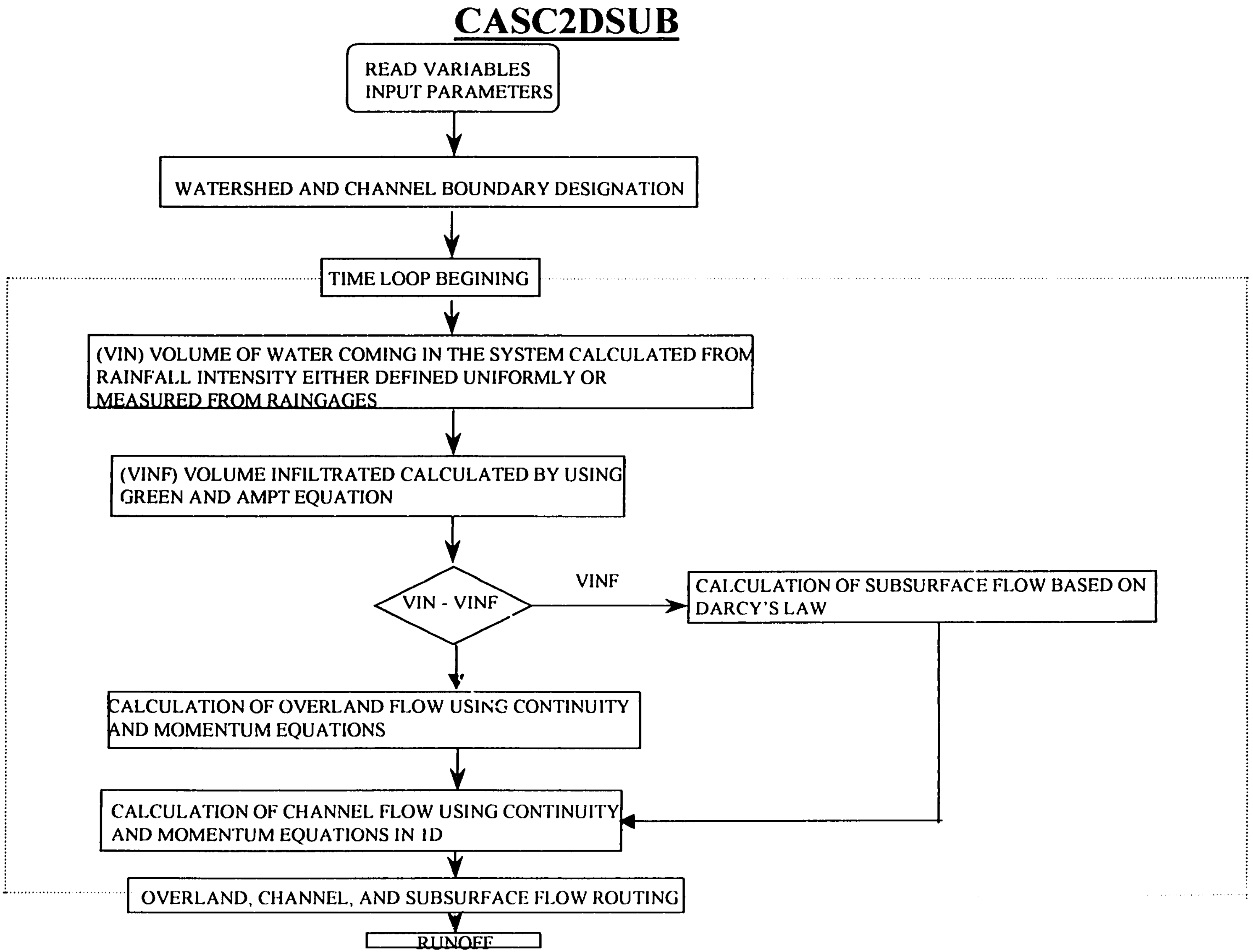


Fig. 3.3: Flow chart for the model CASC2DSUB

SUBSURFACE FLOW CHART

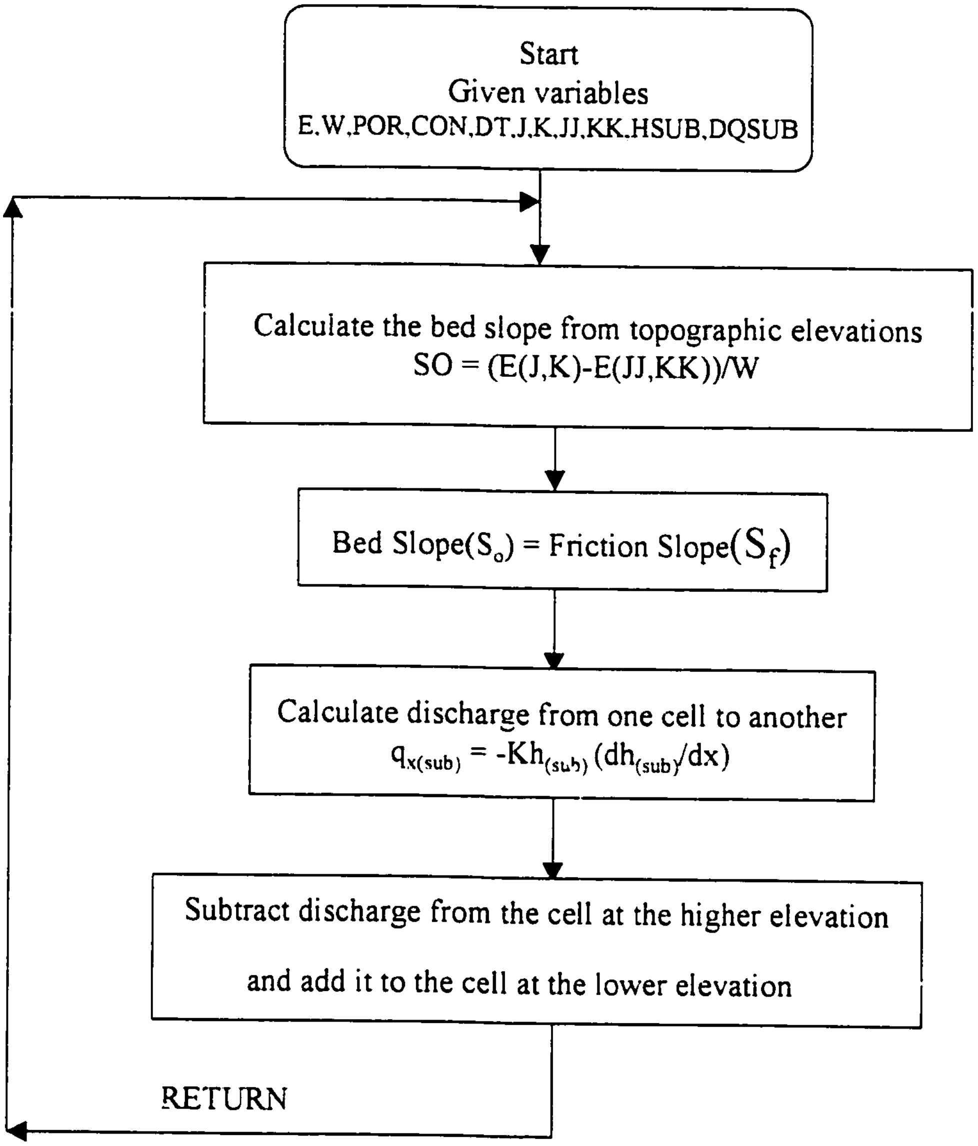
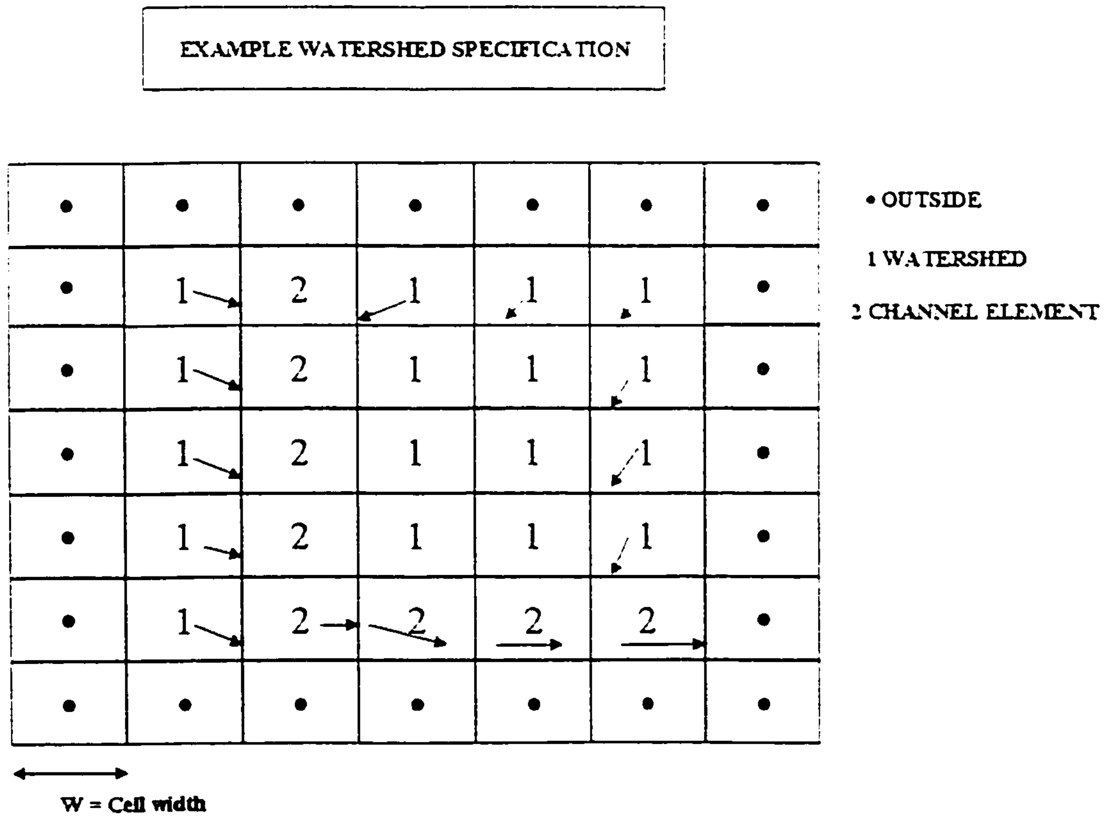


Fig. 3.4 Flow chart for subsurface flow scheme

3.5 APPLICATION AND TESTING ON A SMALL VIRTUAL PLOT

The example watershed is displayed as a square grid of 7x7 (i.e. 7 rows and 7 columns), but the actual designated watershed boundary is only 5x5 (i.e. 5 rows and 5 columns). Thus the actual watershed contains only 25 cells, each having a width of 10 meters. For the modeling purposes, the watershed is subdivided into two types of surfaces, land surface and channel surface based on the number assigned to each of the cells. Number 1 designates the watershed land surface, while number 2 designates the channel surface, and the number 0 stands for "outside the watershed boundary", as shown in Figure 3.5.



●	●	●	●	●	●	●
●	1	2	1	1	1	●
●	1	2	1	1	1	●
●	1	2	1	1	1	●
●	1	2	1	1	1	●
●	1	2	2	2	2	●
●	●	●	●	●	●	●

Figure 3.5: Schematic representation of small watershed with intended water flow

Certain amount of water infiltrates in the ground, corresponding to existing hydraulic conductivities of the soils. This infiltrated water then acts as the input for the calculation of the subsurface flow, which is calculated as the exchange of water mass from a cell to the adjacent cell and the cell directly below it in the predefined grid system. The movement of water is governed by the topographic elevations of the concerned cells.

The response of a small hypothetical watershed to a runoff inducing event is examined with the aid of CASC2DSUB, to test the subsurface flow routine. The observations are focused on the subsurface response when the soil type characteristics are varied. A uniform rainfall intensity of 1.0E-5m/sec is supplied as the input to the system, which leads to the generation of subsurface flow, overland flow, and channel flow. In terms of the water balance on the entire watershed, the volume of water in the subsurface, overland, or the channels depends on the soil type (each having different hydraulic conductivity). For this example watershed, three different soil types have been simulated: clay, which has very low hydraulic conductivity (K=1.0E-11m/sec); sand, which has medium hydraulic conductivity (K=5.0E-4m/sec); and gravel, which has high hydraulic conductivity values (K=3.0E-2m/sec). In each case, the rainfall storm event was simulated for 16.67 minutes, and the response was calculated for 66.67minutes.

The results of the application of the CASC2DSUB model on the virtual watershed are discussed in the following sections.

Depending upon the hydraulic conductivity of the soils, the water infiltrates in the ground. This infiltrated water then acts as the input for the calculation of the subsurface flow, which is calculated as the exchange of water mass from a cell to the adjacent cell and the cell directly below it in the predefined grid system. The movement of water is governed by the topographic elevations of the concerned cells.

The response of a small hypothetical watershed to a runoff inducing event, is examined with the aid of CASC2DSUB to test the subsurface flow routine. The observations are focused on the subsurface response when the soil type characteristics are varied. A uniform rainfall intensity of 1.0E-5m/sec is supplied as the input to the system, which leads to the generation of subsurface flow, overland flow, and channel flow. In terms of the water balance on the entire watershed, the volume of water in the subsurface, overland, or the channels depends on the soil type (each having different hydraulic conductivity). For this example watershed, three different soil types have been simulated: clay, which has very low hydraulic conductivity (K=1.0E-11m/sec); sand, which is of medium hydraulic conductivity (K=5.0E-4m/sec); and gravel, which is of high hydraulic conductivity values (K=3.0E-2m/sec). In each case, the rainfall storm event was simulated for 16.67 minutes, and the response was calculated for 66.67minutes.

The results of the application of model CASC2DSUB on the virtual watershed are discussed in the following sections.

3.5.1 Clay Results

The results obtained after simulating the rainstorm event on a watershed having "clay" as a uniform soil type suggest that the water balance is very well maintained. This is inferred by considering that the total amount of water coming into the system by means of the rainfall event (i= 1.0E-5m/sec for 16.67 minutes) is 882.20 cubic feet (24.97 cubic meters), and the amount of water infiltrating in the ground is very small, as the hydraulic conductivity (k = 1.0E-11m/sec) of clay is very low. Hence most of the water flows out of the watershed (878.118 cubic feet (24.859 cubic meters)), and small amounts of water are left in the channel (3.378 cubic feet (.0956 cubic meters)), and the overland flow (0.6902 cubic feet (1.9539E-02 cubic meters)). Summing up the volume of water from the various locations on the watershed (i.e., channel, overland and the outlet), it is observed that the error is only 1.4E-3 percent, as observed in Table 3.2.

Table 3.2:Results Obtained for soil type =CLAY in cubic feet

1	VOLUME IN (ft^3)	882.20
2	VOLUME INFILTRATED (ft^3)(2)=(3) + (4)	0.0035
3	VOLUME OF WATER RETAINED IN THE SUBSOIL (ft^3)	0.0024
4	SUBFLOW CONTRIBUTION TO SURFACE VOLUME (ft^3)	0.0011
5	SURFACE VOLUME (ft^3) (5) = (6) + (7)	4.0689
6	OVERLAND CONTRIBUTION TO SURFACE VOLUME (ft^3)	0.690
7	CHANNEL CONTRIBUTION TO SURFACE VOLUME (ft^3)	3.3787
8	TOTAL VOLUME OF WATER OUT (ft^3) AT THE END OF 66.67 min.	878.12
9	SUM(VOLUME RETAINED+SURFACE VOLUME+VOLUME OUT) (ft^3) (9)=(3)+(5)+(8)	882.19

Row 5 in table 3.2 represents the total volume of water on the surface of the watershed. This volume of water could be on the overland (row 6) or in the channel (row 7), hence row 5 represents the volume of water that is the summation of rows 6 and 7. Row 9 does the mass balance by summing up the volume of water, which after rainfall has moved to either the overland, subsurface, channels, or out of the watershed with time. Hence row 9 is the result of adding rows 3, 5, and 8.

The water balance graph for clay (Figure 3.6) indicates that clay, because of it's low hydraulic conductivity, does not allow much water to infiltrate into the subsurface, and overland flow is the major component that dominates the watershed response. With the passage of time the major portion of water flows out from the outlet, which is indicated by the "vout" line in Figure 3.6. For the clay soil type, the water balance matrices may be observed in the file "clay2bugsub" in Appendix D.

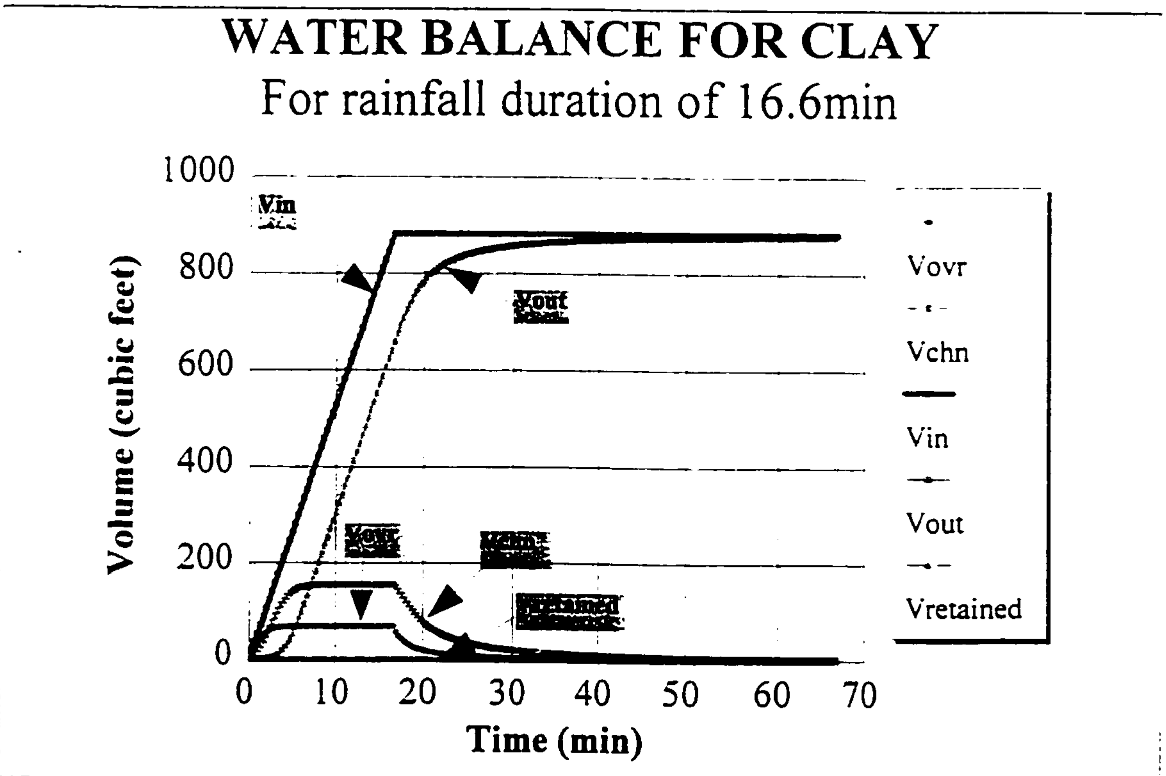


Figure 3.6 : Graphic representation of results on soil type clay

3.5.2 Sand Results

With "sand" (k = 5.0E-4m/s) as the uniform soil type, the watershed is subjected to a uniform rainfall intensity of 1.0E-5m/s for 16.67minutes. It is observed that the water balance is well maintained, and the error is 1.5E-3 percent. In this case almost all of the water infiltrates into the subsurface. Some is retained in the subsurface soil matrix (484.65ft^3), and some of it flows into the channel as subsurface flow. In this case the overland portion is non-existent. Thus subsurface flow dominates the response of the watershed, as observed from Table 3.3 and Figure 3.7. Also, the volume of water flowing out of the system from the watershed outlet is not as much as in the case of clay or gravel. The water balance matrices for the sand soil type may be observed in the file "sand2bugsub" in the appendix D.

Table 3.3: Results Obtained for the soil type = SAND in cubic feet

1	VOLUME IN (ft^3)	882.20
2	VOLUME INFILTRATED (ft^3) (2) = (3) + (4)	882.18
3	VOLUME OF WATER RETAINED IN THE SUBSOIL (ft^3)	485.65
4	SUBFLOW CONTRIBUTION TO SURFACE VOLUME (ft^3)	396.54
5	SURFACE VOLUME (ft^3) (5) = (6) + (7)	17.91
6	OVERLAND CONTRIBUTION TO SURFACE VOLUME (ft^3)	0.00
7	CHANNEL CONTRIBUTION TO SURFACE VOLUME (ft^3)	17.91
8	TOTAL VOLUME OF WATER OUT (ft^3) AT THE END OF 66.67 min	378.62
9	SUM(VOLUME RETAINED+SURFACE VOLUME+VOLUME OUT) (ft^3) (9)=(3)+(5)+(8)	882.188

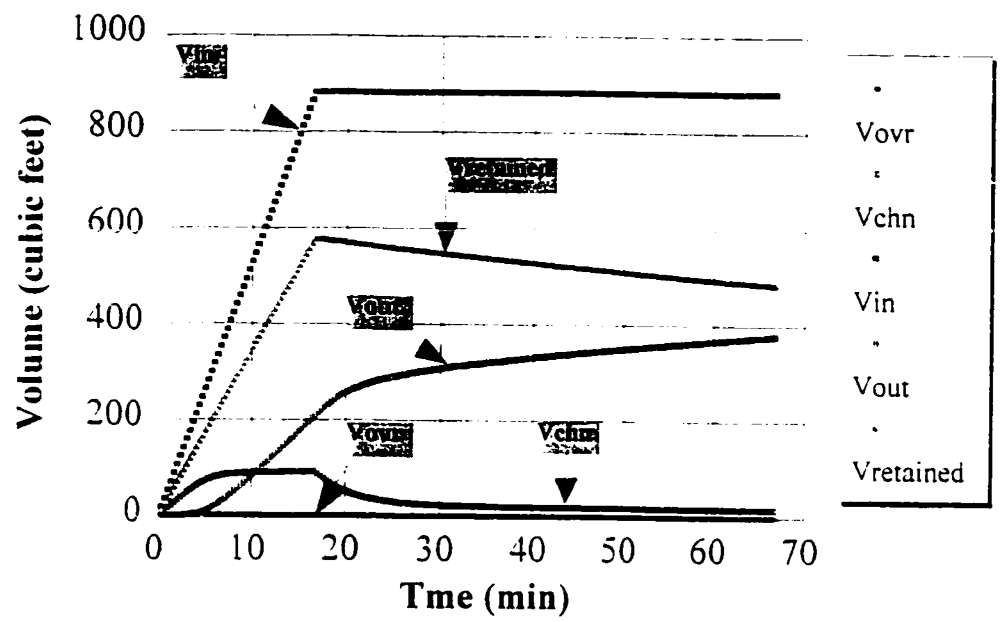


Figure 3.7: Graphic representation of results on soil type sand

3.5.3 Gravel Results

In this case, the whole watershed has gravel (k = 3.0E-2m/s) as the uniform soil type, and is subjected to a uniform rainfall intensity of 1.0E-5m/s for 16.67 minutes. Gravel has the highest hydraulic conductivity. Thus not only does all of the water infiltrate, but most of the water is routed as subsurface flow into the channel and out of the watershed. In this case, there is hardly any retention of water in the subsurface soil matrix. Once again it is observed that the water balance is maintained, and the error is only 1.49E-3 percent, as observed in Table 3.4

Table 3.4: Results Obtained for soil type = GRAVEL in cubic feet

1	VOLUME IN (ft^3)	882.20
2	VOLUME INFILTRATED (ft^3) (2) = (3) - (4)	882.18
3	VOLUME OF WATER RETAINED IN THE SUBSOIL (ft^3)	0.0013
4	SUBFLOW CONTRIBUTION TO SURFACE VOLUME (ft^3)	882.186
5	SURFACE VOLUME (ft^3) (5) = (6) - (7)	3.445
6	OVERLAND CONTRIBUTION TO SURFACE VOLUME (ft^3)	0.00
7	CHANNEL CONTRIBUTION TO SURFACE VOLUME (ft^3)	3.445
8	TOTAL VOLUME OF WATER OUT (ft^3) AT THE END OF 66.67 min	878.74
9	SUM (VOLUME RETAINED-SURFACE VOLUME-VOLUME OUT) (ft^3) (9) = (3)-(5)-(8)	882.189

Again it is observed that the subsurface is the major component dominating the response of the watershed having high hydraulic conductivity. Figure 3.8 indicates that with high hydraulic conductivity, most of the water flows out of the outlet.

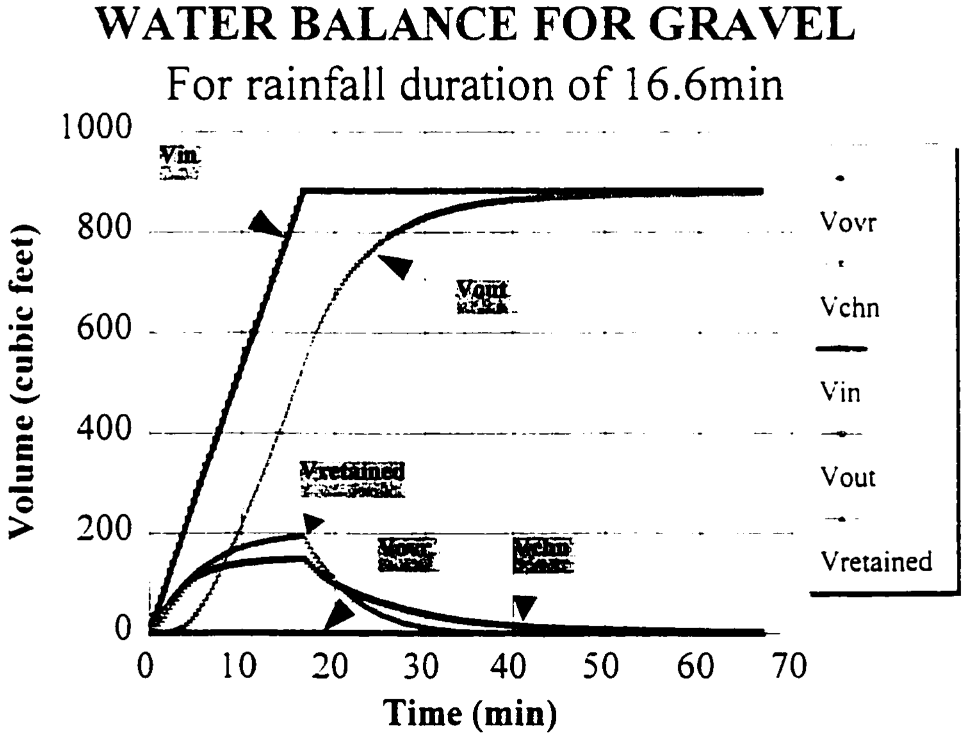


Figure 3.8: Graphic representation of results on soil type gravel

When conducting the water balance for a simulation for example soil type Gravel, the water at particular time step can be either on overland, channel, or subsurface.

File "Gravel2bugsub" (Appendix D) shows, in matrix form, the height of water in each cell at a particular time step. For demonstration purposes, selection is made for early time step, after peak and late time step.

In early time step it is observed that most of the water has infiltrated into the soil, so there is no overland flow as depicted by the overland flow matrix, while water is observed in the channel cells, with water depth increasing towards the outlet. The subsurface matrix shows the depth of water in each cell of the watershed except the channel cells. The infiltrated water matrix shows the total infiltrated depth of water at an early time step.

At peak, the maximum depth of water is observed in each of the matrices. After peak the depth of water starts to decrease in each case as the rainfall is stopped and there is no incoming water to the system. At later time steps, it is observed that most of the water has gone out of the system (watershed), and the lowest water depth is observed in each of the cells.

3.5.4 Simulation effect on different soil types

Figure 3.9 is indicative of how soil type affects the response of a watershed in terms of discharge generated with time.

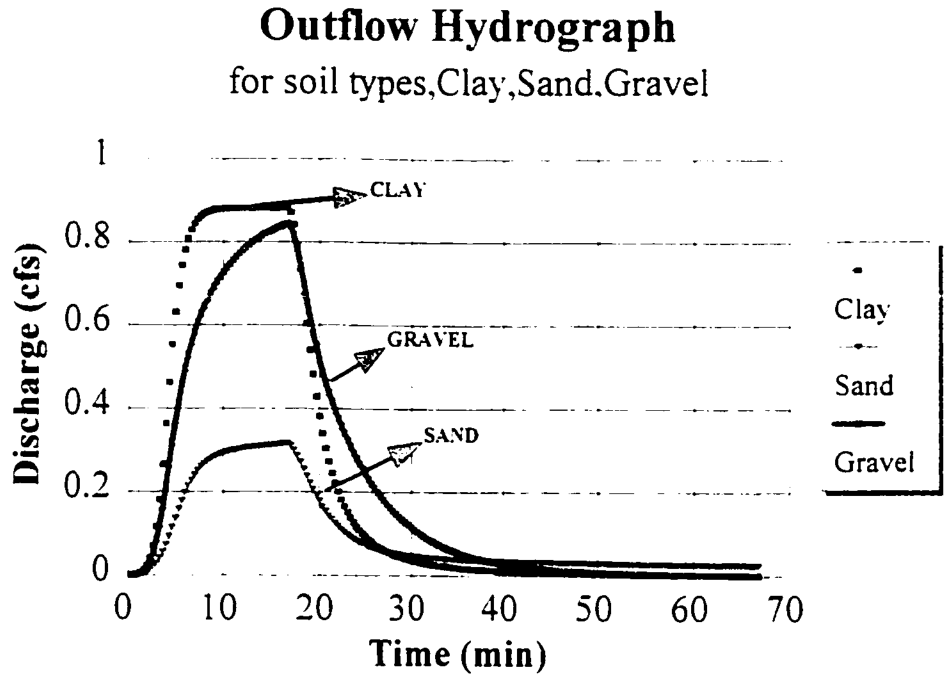


Figure 3.9: Comparison of outflow hydrographs for clay,sand,and gravel

The outflow hydrograph (Fig 3.9) shows that for clay (very low hydraulic conductivity), hardly any water infiltrates in the soil, and most of the water flows out as overland flow. This is also substantiated by Fig 3.10, which shows no surface retention for clay.

In the case of sand, the water infiltrates, but the hydraulic conductivity of the sand is not so high. Thus, there is not much lateral movement of water, and as a result, not all of the water flows out of the watershed, as observed in Fig 3.9. However for sand the subsurface water retained is maximum as observed in Fig 3.10.

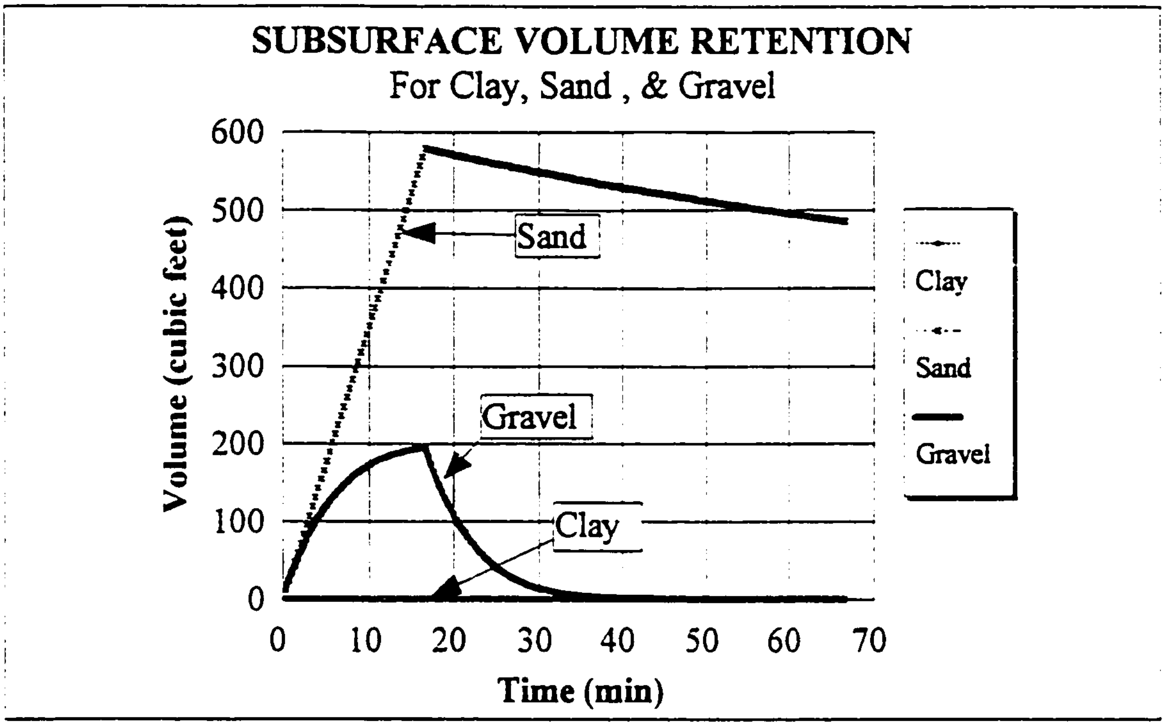


Figure 3.10: Water retention trend of soil types – clay, sand, gravel

In the case of gravel, with high hydraulic conductivity, all the water infiltrates, moves laterally and flows into the channel. This is observed in Fig 3.9 as the curve label "Gravel". Also the subsurface retention increases initially to a maximum of 200 ft^3, but after 17 minutes, all the retained water flows out to the channel, as observed in Fig 3.10. A comparison of the results may be observed in Table 3.5.

Table 3.5: Comparison of results on simulating soil types clay, sand, and gravel.

S.No	VOLUMES	CLAY	SAND	GRAVEL
1	Hydraulic Conductivity used (m/sec)	1.0E-11	5.0E-4	3.0E-2
2	volume in (ft^3)	882.20	882.20	882.20
3	volume infiltrated (ft^3)	0.0035	882.189	882.189
4	volume of water retained in the subsoil (ft^3)	0.0024	485.65	0.00124
5	Subsurface flow contribution to surface volume (ft^3)	0.001	396.54	882.186
6	surface volume (ft^3) (6 = 7+8)	4.069	17.91	3.445
7	overland contribution to surface volume (ft^3)	0.690	0 .00	0.00
8	channel contribution to surface volume (ft^3)	3.378	17.909	3.445
9	total volume of water out (ft^3) at the end of 66.67 min	878.12	378.628	878.743
10	sum(volume retained+surface volume+volume out) (ft^3) (10=4+6+9)	882.19	882.189	882.189

The results obtained after the implementation of the CASCSUB2D model on the example watershed indicates that the water balance is well maintained for each of the soil types. The volume of water coming into the system (vol. in for clay = 882.2ft^3) in each case is almost equal to the sum of the volume of water distributed as overland, subsurface, channel, and out of the watershed (e.g. SUM for clay =882.18ft^3). The significant contribution of model subroutine SUBFLO to the rainfall-runoff storm event can be best observed in the highly permeable shallow soil layer (e.g. gravel). The flow of water in each of the watershed sections (i.e., the overland, the channel, and the subsurface) can be seen in Appendix D for each of the soil types.

CHAPTER IV

FIELD APPLICATION OF SUBSURFACE FLOW MODEL

4.1 GOODWIN CREEK WATERSHED

The Goodwin Creek watershed (Fig 4.1) was selected as the test site for the subsurface model CASC2DSUB. The watershed has been used as a test site to validate the model developed. The watershed is located in the loess-capped hills of the Yazoo river basin of northern Mississippi, with its outlet at latitude 89° 54' 50'' and longitude of 34° 13' 55''. The watershed drains an area of 21.5 km^2 in Panola County, Mississippi.

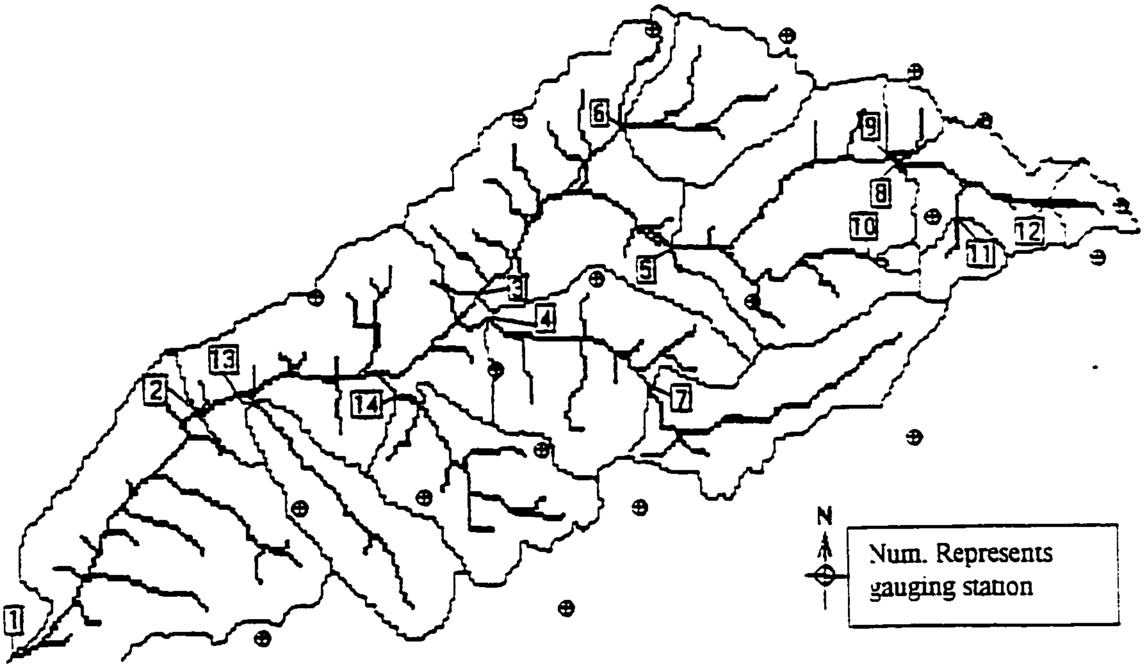


Figure 4.1: Goodwin Creek watershed map with raingage locations

The topographic elevations range from 71m to 128m above mean sea level as shown in Figure (4.2). The climate is hot and humid in the summer, and mild in the winter. The annual average temperature in the area is about 17 degrees Celsius, and the average annual rainfall is about 1399 mm per year. The rainfall on the watershed is continuously monitored by a network of 17 weighing precipitation gages, located both inside and outside the periphery of the watershed.

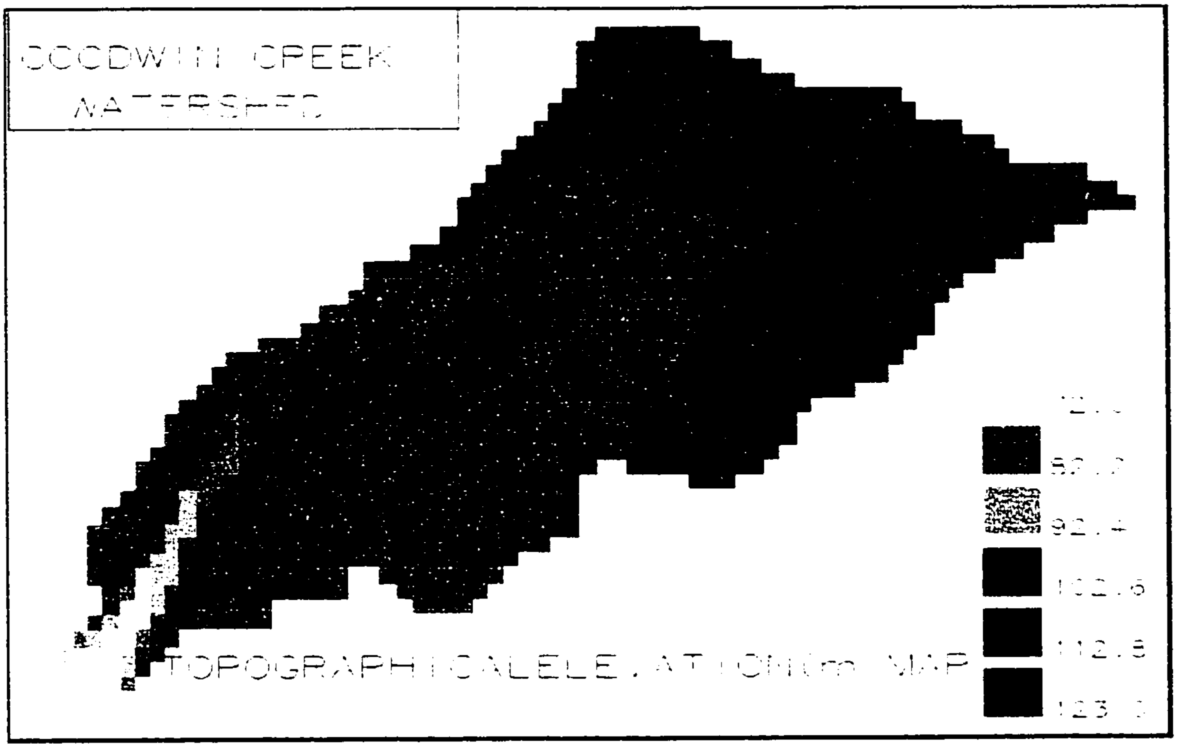


Figure 4.2: Graphic representation of Goodwin Creek elevation map

In overland regions, 50% of the basin has a slope less than 0.02 and 15% of the regions have slopes greater than 0.03. The channel slopes range from 0.0017 to 0.017, with an average channel slope of 0.004. Land use types are described as 13%

cultivated, and 87% pasture or forest. The soil distribution is comprised of silt loam and fine sandy loam (Figure 4.3). The general description of the watershed has been presented by Grissinger and Murphey (1986). The geology of the region, and types of formations have been detailed by Grissinger, Murphey, and Little (1981).

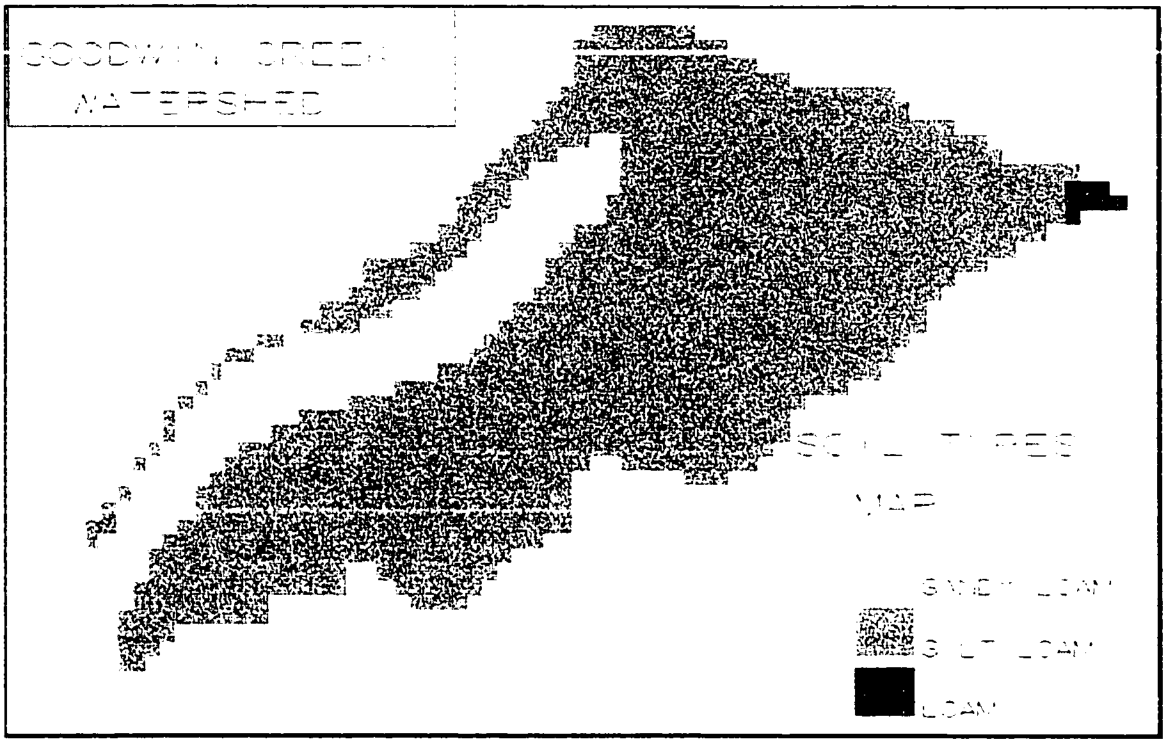


Figure 4.3: Graphic representation of Goodwin Creek soil distribution

4.2 MODEL CALIBRATION

The model was tested in segments, which is to say that the response of the watershed was observed for the specified conditions of uniform rainfall intensity, single soil type, and uniform resistance factor defined by Mannings n, for the surface and the subsurface. Once the program depicted the uniform functionality in terms of watershed response, the actual rainstorm was used for model calibration.

For the model to be applied to a watershed, it must be calibrated. If historical data is available, then the simulated output can be compared to the observed data. Thus, calibration is the process of adjusting the parameter values to improve the agreement between the simulated and the observed data. The parameter identification for the model has been accomplished manually by the trial and error.

The model was calibrated on the historical rainfall storm event that occurred on October 17, 1981 (Fig. 4.4).

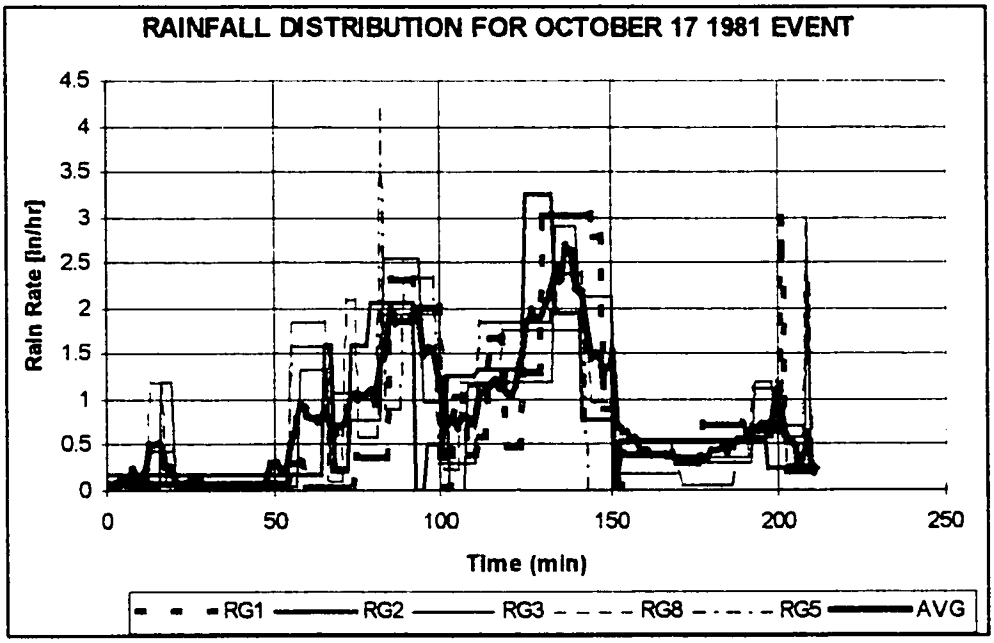


Figure 4.4: Graphic representation of rainfall distribution of October 17, 1981 event

The storm commenced at 9:19pm, and continued for a duration of 3.5 hours. Rainfall data was recorded at 17 raingages distributed throughout the watershed, and the rainfall preceding the event was negligible. The average rainfall rate was .811 in/hr (5.72E-6 m/s).

The model calibration was approached by fitting the simulated hydrograph at the outlet to the observed hydrograph at the outlet Fig 4.5. To achieve the purpose, parameters such as detention storage (S_d) accounting for the precipitation detained by the foliage and the trees; soil characteristics such as hydraulic conductivity (K_s), capillary pressure (H_f), and initial soil moisture deficit (M_d); influencing the infiltration rates, and the Mannings roughness coefficients, such as n_{ov} in overland and n_{chan} in the channel for calculation of discharge rates were taken in to consideration.

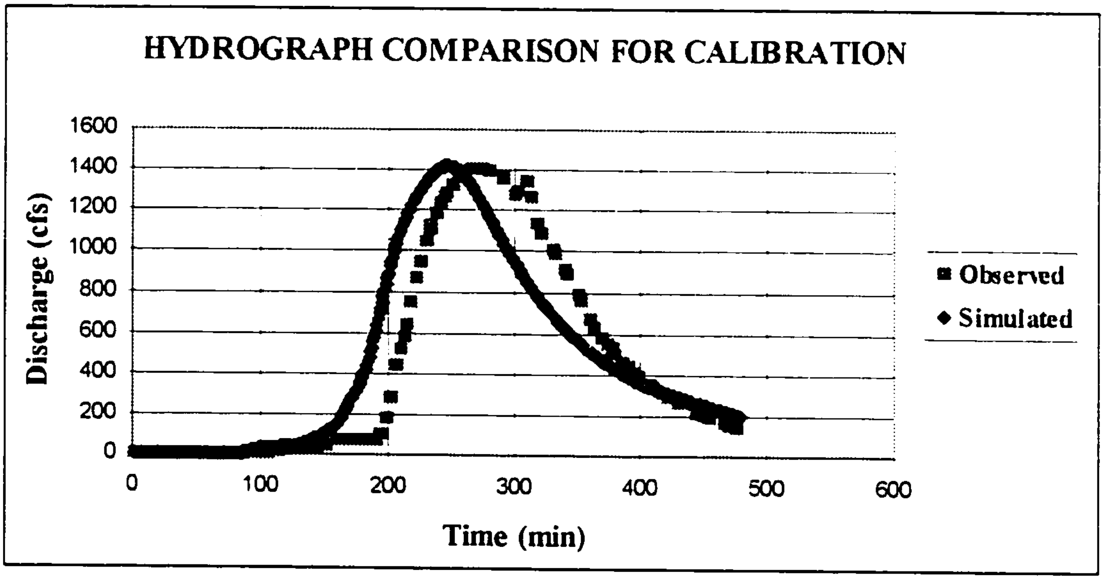


Figure 4.5: Graphic comparison of simulated vs observed hydrograph

It is observed from Fig. 4.5 that the simulated hydrograph follows the same trend as the observed hydrograph. The peaks observed in the simulated and observed hydrograph are comparable with the observed peak seen at 1405 cfs at 266 minutes after the rainfall storm event, while the simulated peak is at 1417 cfs at 246 minutes. The simulated hydrograph achieves peak discharge 20 minutes earlier than the observed hydrograph, and this time lag is reflected in the rising as well as the falling limb of the two hydrographs.

Sensitivity analysis was performed on CASCSUB2D model using hydraulic conductivity, soil moisture content and capillary pressure as the parameters. It was observed that soil moisture content and capillary pressure were hardly influential compared to the hydraulic conductivity as the driving force for the movement of water.

4.3 GRAPHIC REALIZATION

The model is formulated for the UNIX environment, and is compatible for such machines as Dec-Vax, Sun-solaris, and Hp-ux. For the program CASC2DSUB to run it must access specific input files to read in the information. The file "data1" (Appendix C) inputs parameter specifications such as the grid size, the width of the grid cells, outlet coordinates, soil types, infiltration parameters, hydraulic conductivity, capillary pressure, and soil moisture content. This information is detailed in the source code (Appendix A) itself. In addition, specific information such as watershed shape is obtained from file shap.dat (Appendix C). The value of 0 is indicative of the outside watershed area, while 1 is the watershed area. The channel shape and location are obtained from chn.dat file (Appendix C), and the topographic elevations are stored in the elavg.dat file. The soil types (file "soil.dat") are numbered as 1,2, or 3 depending upon the number of soils present in a particular watershed, and the soil parameters are located in data1 file. Similarly the roughness coefficient Manning n (file "iman.dat") is also represented as numbers 1,2,3, and so forth depending upon different soil types. However the actual values of roughness are input in the data1 file. The rainfall intensity values recorded at each of the 17 raingage stations are stored in the file "rain.dat", and the location of the raingages is in the file "rainga.dat." The output is generated in terms of multiple files. The *.prn file displays the discharge in cfs with time, where * stands for a specific event name. Also, this file lists the total amount of water coming into the system, the amount of water in the overland, subsurface, channels, and out of the watershed. A sample of such a file can be observed in Appendix C. The output also generates ASCII files representing the depth of water in each cell of the grid for each of the designated hydrological processes at specified time. For example hsub1 at 10 minutes of simulation, hsub2 at 20 minutes of simulation, and so on. The output files then are used as the input for the graphics generating programs which convert and structure the ASCII output into a graphic realization.

The CASCSUB2D visual display of the simulation in the GRASS4.1 environment is achieved first by converting the ASCII files to raster (cell-based) files. This can be achieved by GRASS command such as "r.in.ascii input=file1 output=file2", where file1 is the input ASCII file and file2 is the output raster file. Once the raster file is produced, it can be visualized in the GRASS monitor by the command "d.rast file2." This allows the projection of one specific file at one instant of time, but if continuous projection of an ongoing process is required, a program needs to be developed. Also, the main visualization monitor frame can be subdivided in terms of 9 different frames. The positioning of each of the frames is specified in the program graph.f, with each grid frame representing a specific physical phenomena or watershed characteristic. In this way, simultaneous visualization of each of the ongoing process is achieved. The program graph.f (Appendix A) shows this composition. The visual animation growth of a specific process is achieved by continuous overlaying of user-defined frames of that particular process. A schematic of various active and stationary CASC2DSUB grid frames is shown in Fig.4.6. The top row of grid frames is stationary, (i.e., the frames do not change with time) and displays only the spatial distribution of Goodwin Creek watershed aspects such as Manning n, soil type, and topographical elevations. The middle row frames vary with time, hence are dynamic in nature. The first frame in the middle row displays the rainfall intensity at the specified time step, computed using the rainfall data from the raingages and interpolated for each grid cell using the inverse distance squared method. The second frame in the middle row displays the infiltration depth of water. based on the Green-Ampt infiltration scheme. The third frame in the middle row displays the overland flow depth, based on the St.-Venant equations. The third row displays the dynamic nature of the subsurface and the channel flow. The first frame of the third row displays subsurface flow based on Darcy's flow equation. The second frame of the third row displays the channel flow based on the St.-Venant equation.

Manning's "n" Distribution	Soil Texture Distribution	Topographical Elevation Distribution
Rainfall Intensity Distribution	Infiltration Depth Distribution	Overland Depth Distribution
Subsurface Depth Distribution	Channel Depth Distribution	Header

Fig 4.6: Schematic of CASCSUB2D graphical grid presentation

Once the graphic visualization is achieved, the legends for each of the frames. and the color schemes for each of the processes are created in the files *_colr, where * represents the name of specific process, for example hsub_colr, (color scheme for subsurface), which on running the program creates color schemes for each of the hsub files such as hsub1, hsub2, and so on. Also, the headings and positioning of the titles, and color boxes is accessed through files *_map, where * stands for the name of specific process.

The simulation is compared with the observed data of the specified storm on October 17, 1981. It is observed from the Fig (4.5) that the simulation result is consistent with the observed data.

The model was also simulated for the uniform soil type with hydraulic conductivity of 3.4E-2m/s with variable rainfall intensity rainstorm of October 17, 1981 for a period of 1.67 hours. The model was simulated for a total of 125 hours. In this case all of the water has infiltrated in the subsurface, and there is no water on the surface. Figures 4.7 -- 4.24 show the graphic progression of the subsurface slowly increasing in subsurface depth of water, and with time draining out of the subsurface and the channels.

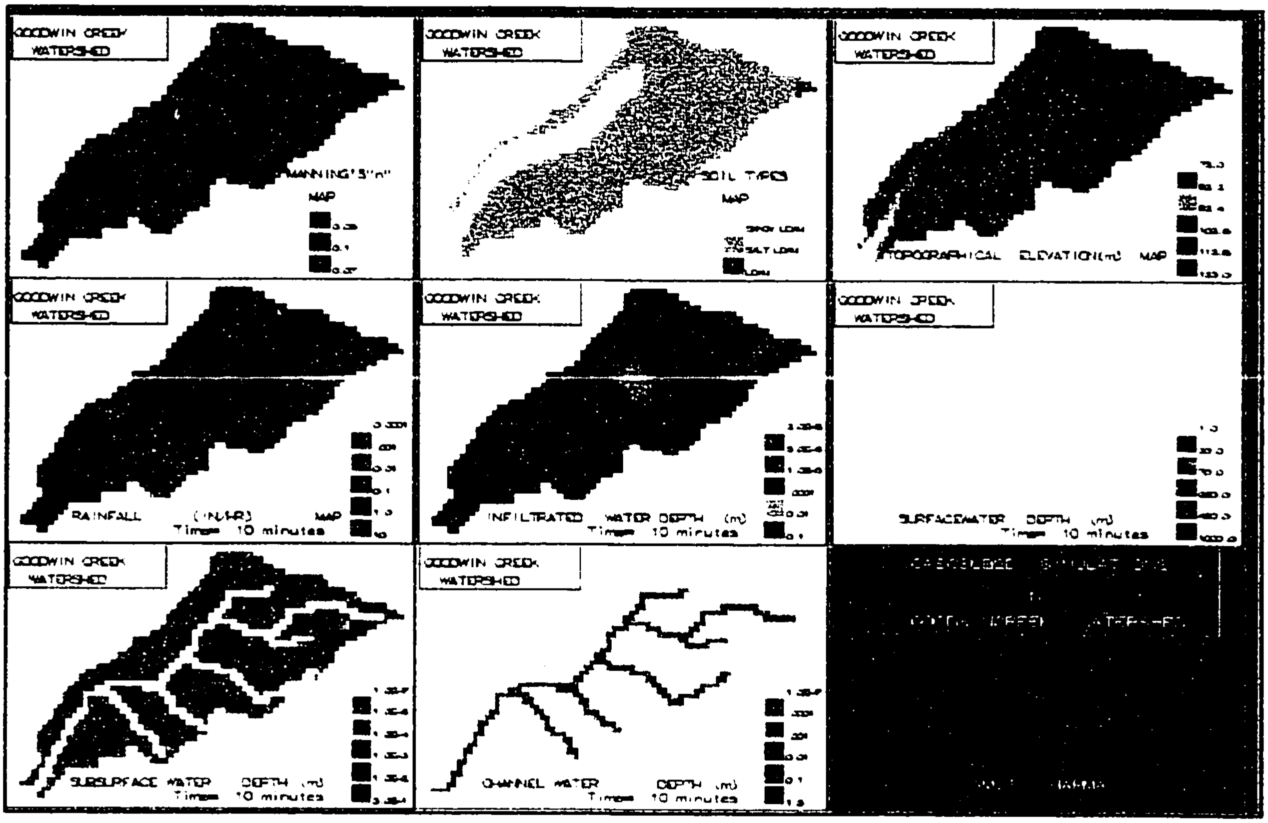


Figure 4.7a: Graphic representation of continuous simulation frame at 10 minutes

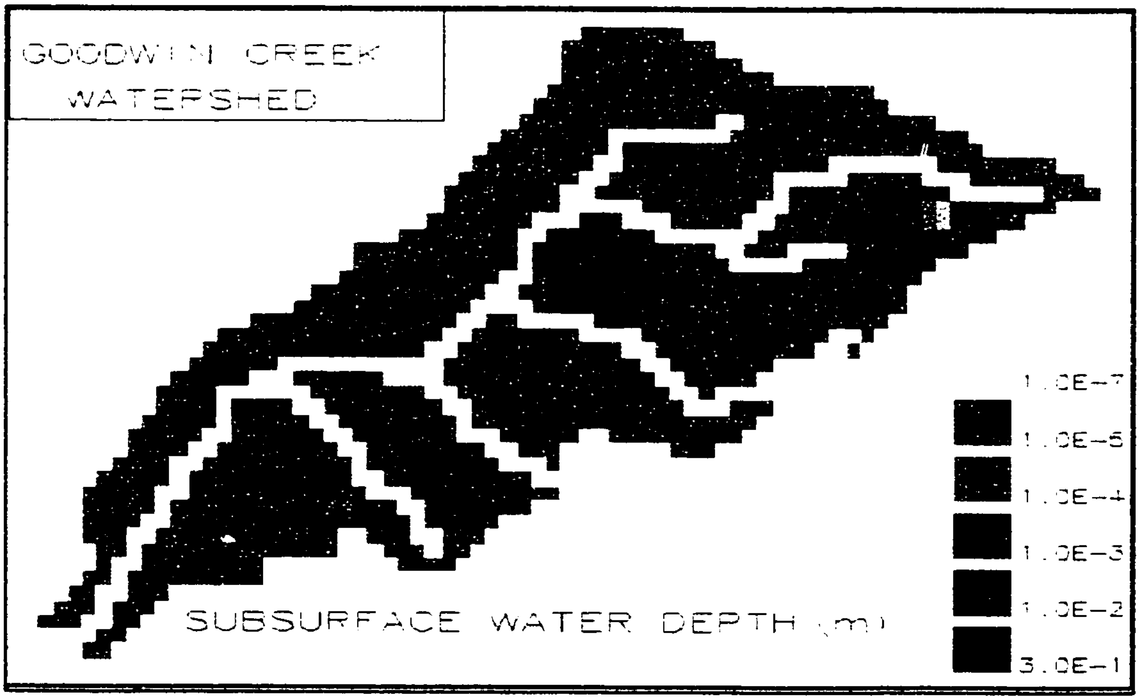


Figure 4.7b: Subsurface flow representation at 10 minutes

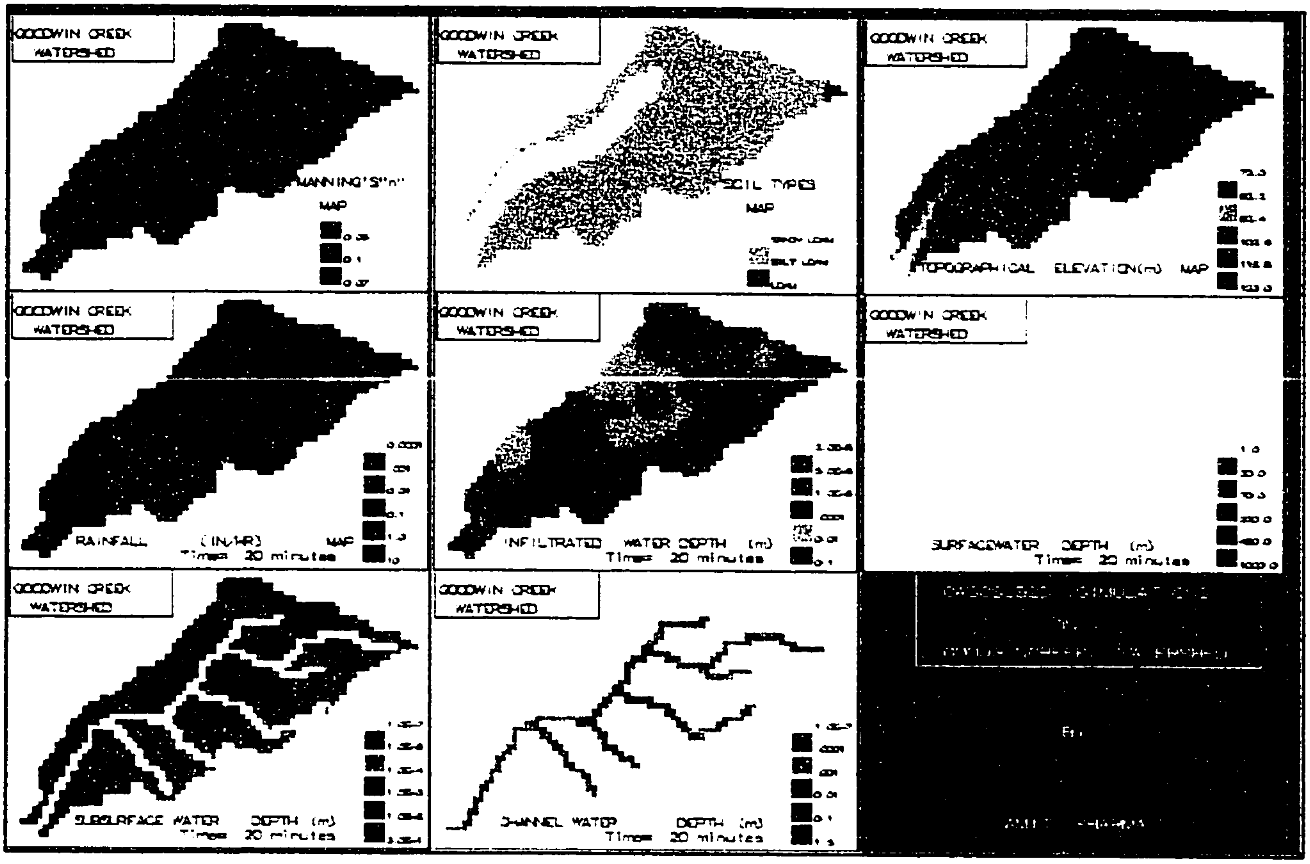


Figure 4.8a: Graphic representation of continuous simulation frame at 20 minutes

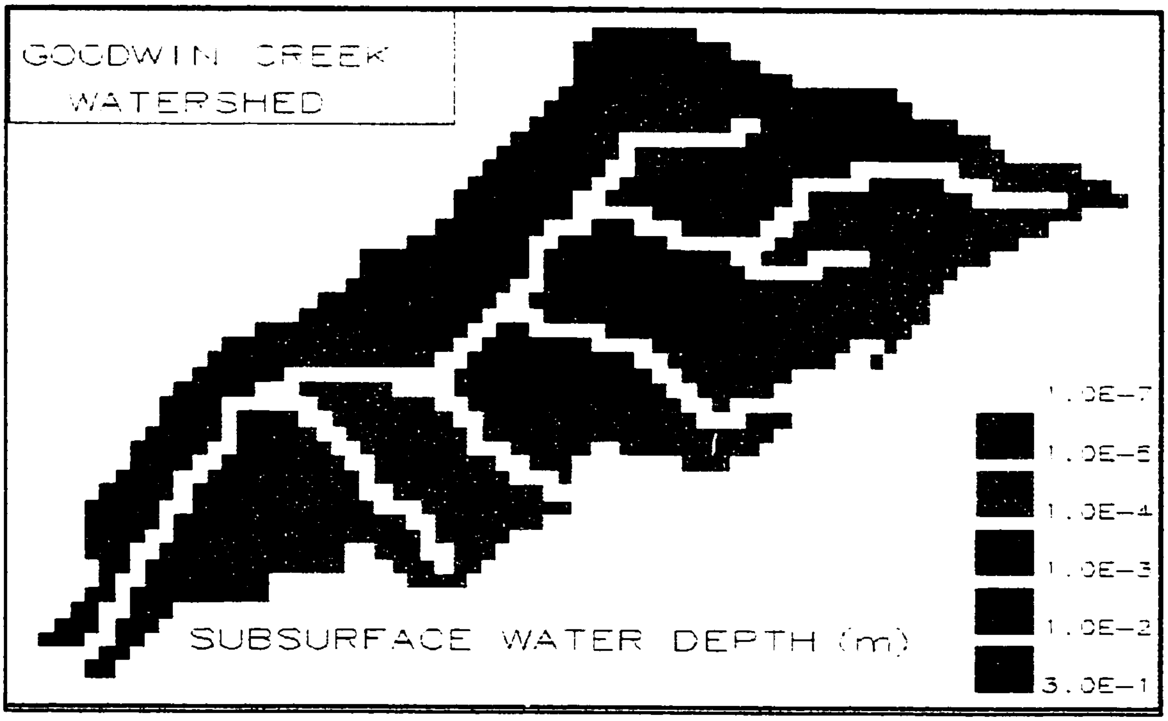


Figure 4.8b: Subsurface flow representation at 20 minutes

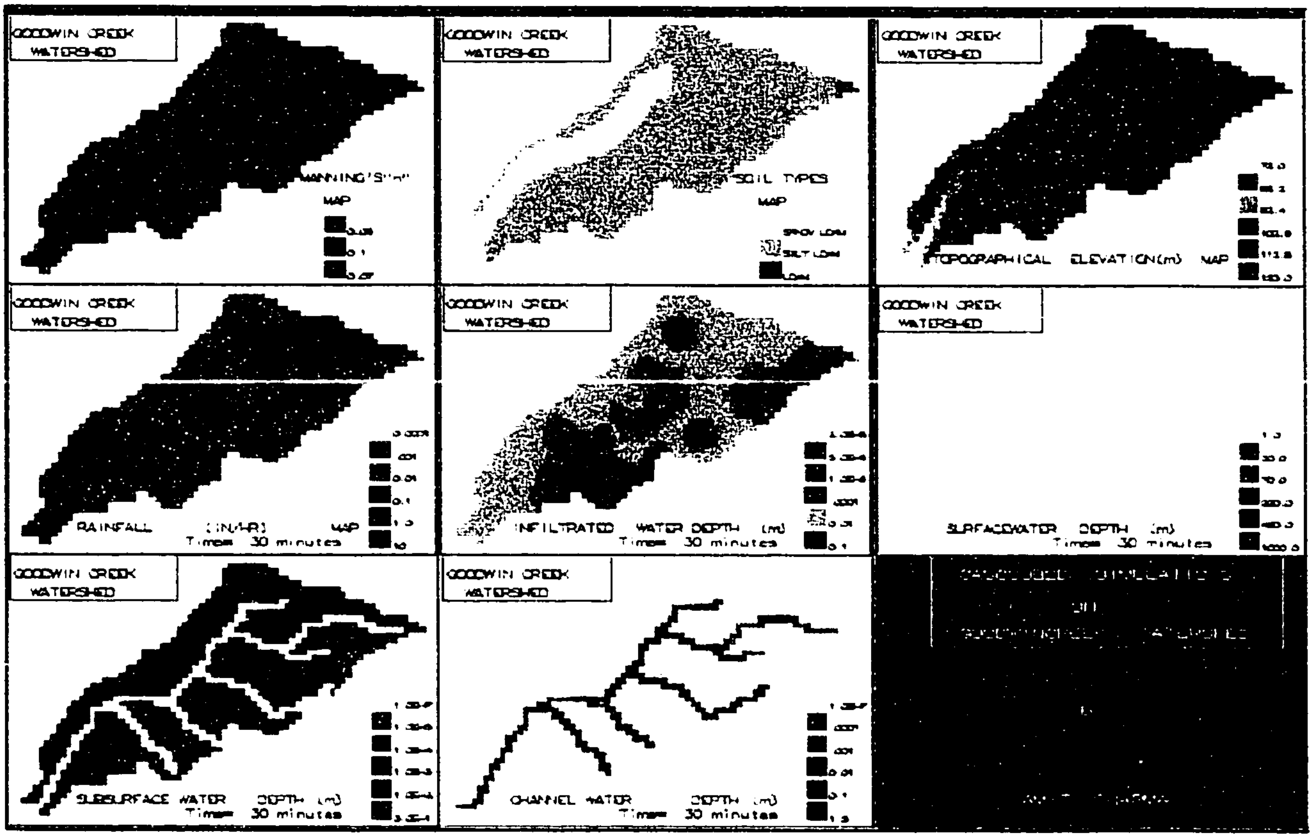


Figure 4.9a: Graphic representation of continuous simulation frame at 30 minutes

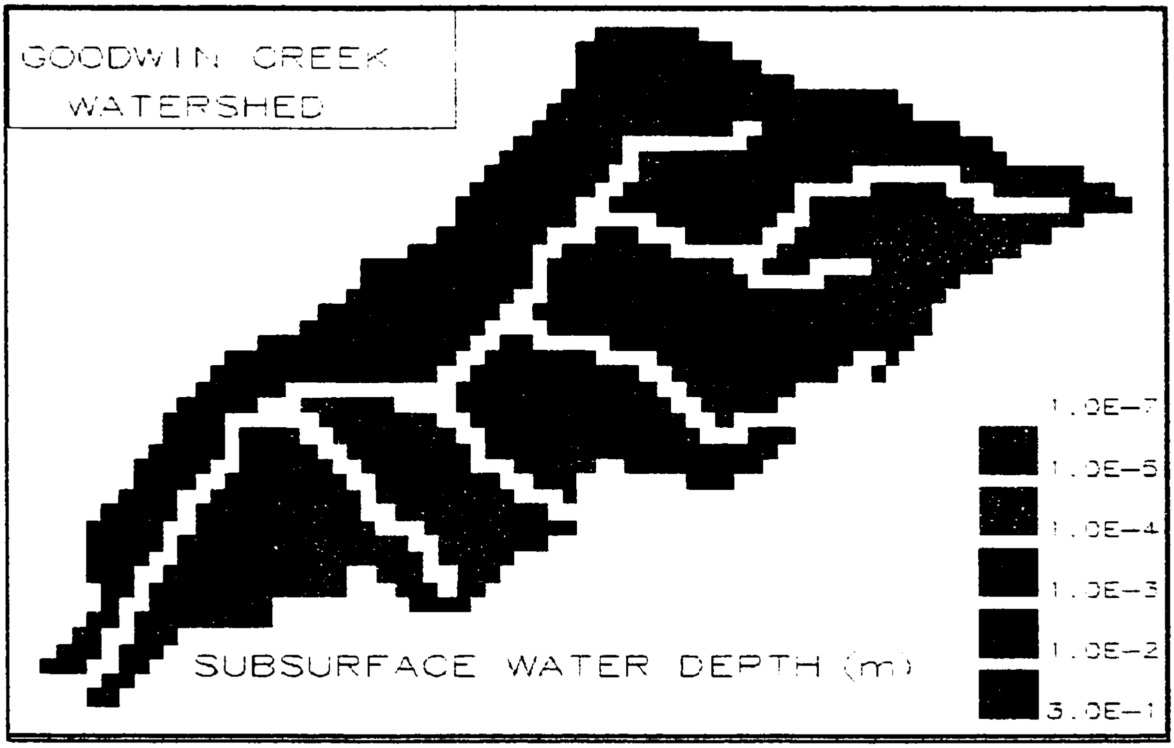


Figure 4.9b: Subsurface flow representation at 30 minutes

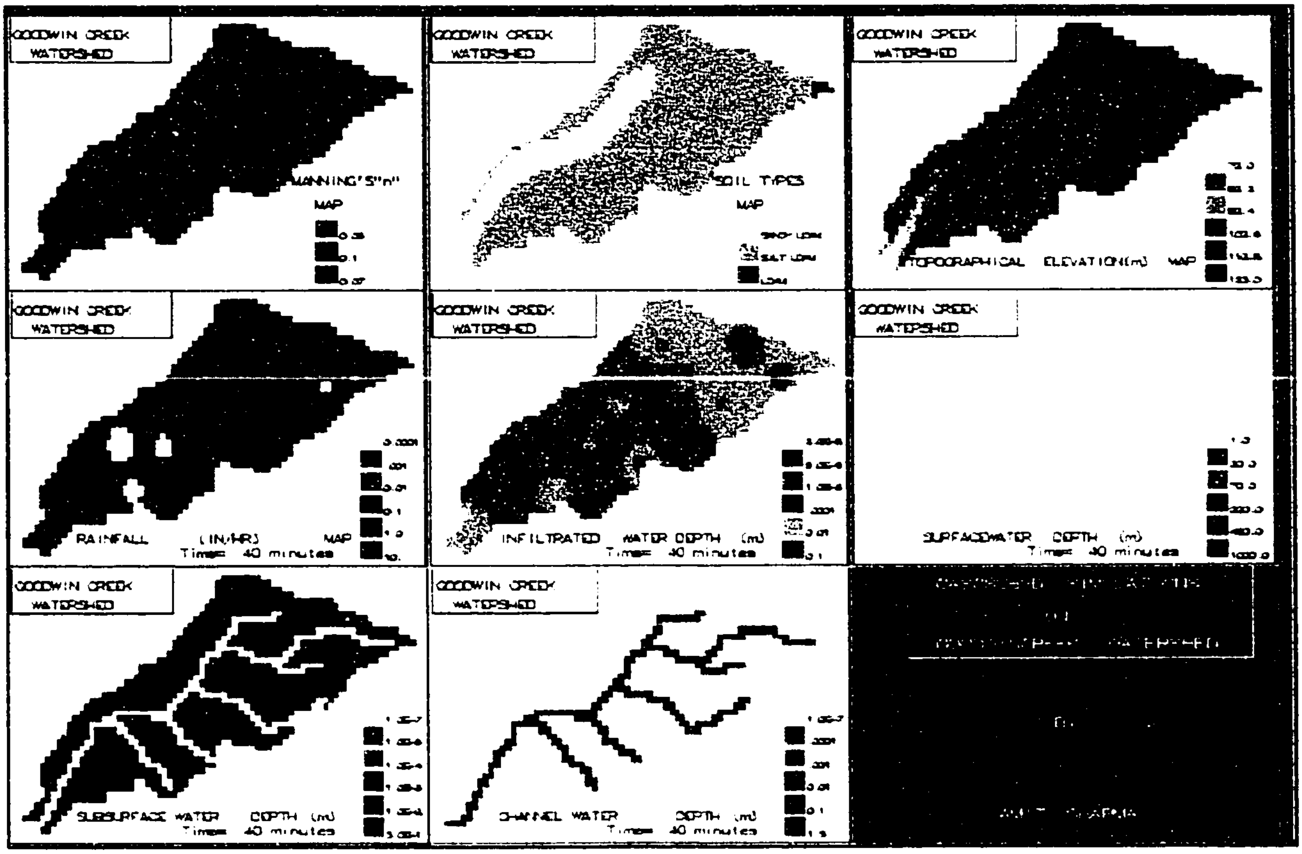


Figure 4.10a: Graphic representation of continuous simulation frame at 40 minutes

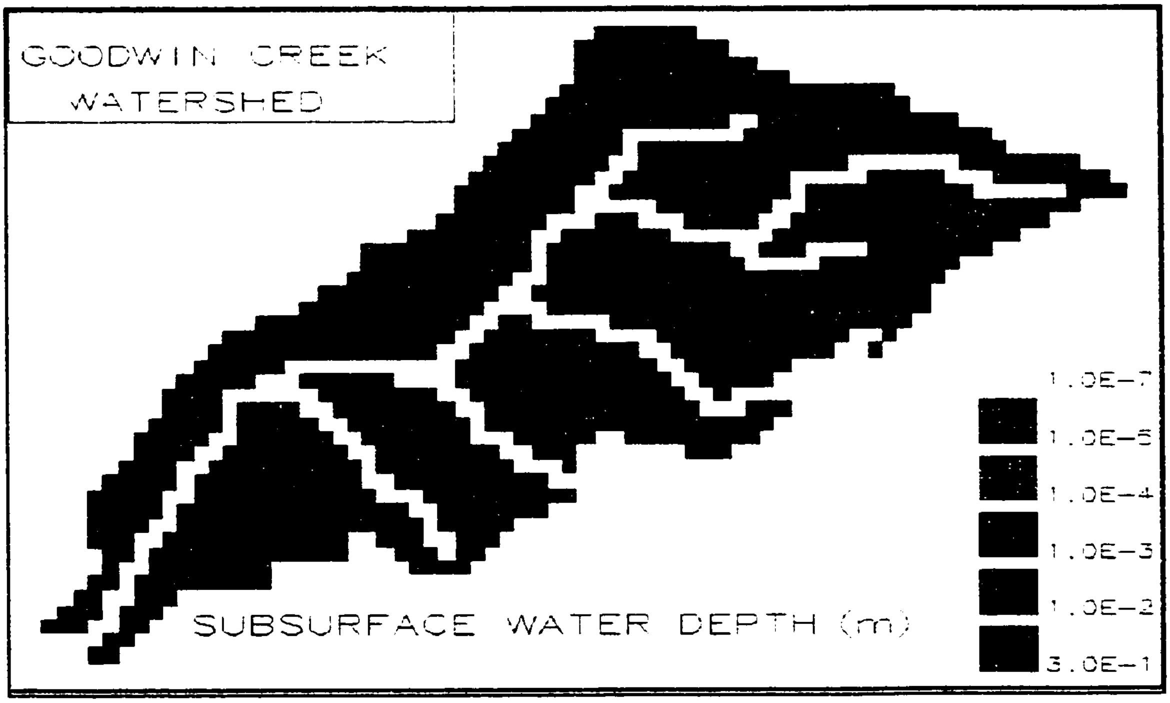


Figure 4.10b: Subsurface flow representation at 40 minutes

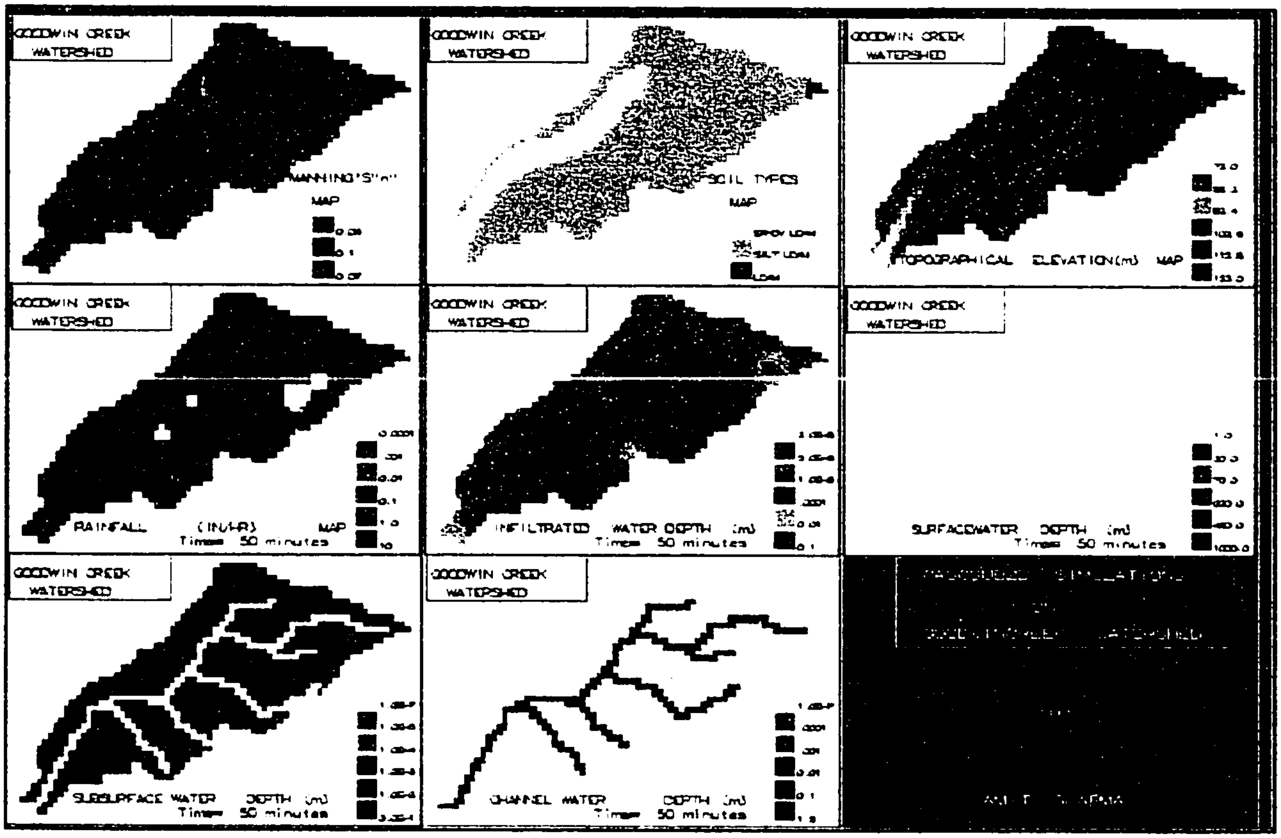


Figure 4.11a: Graphic representation of continuous simulation frame at 50 minutes

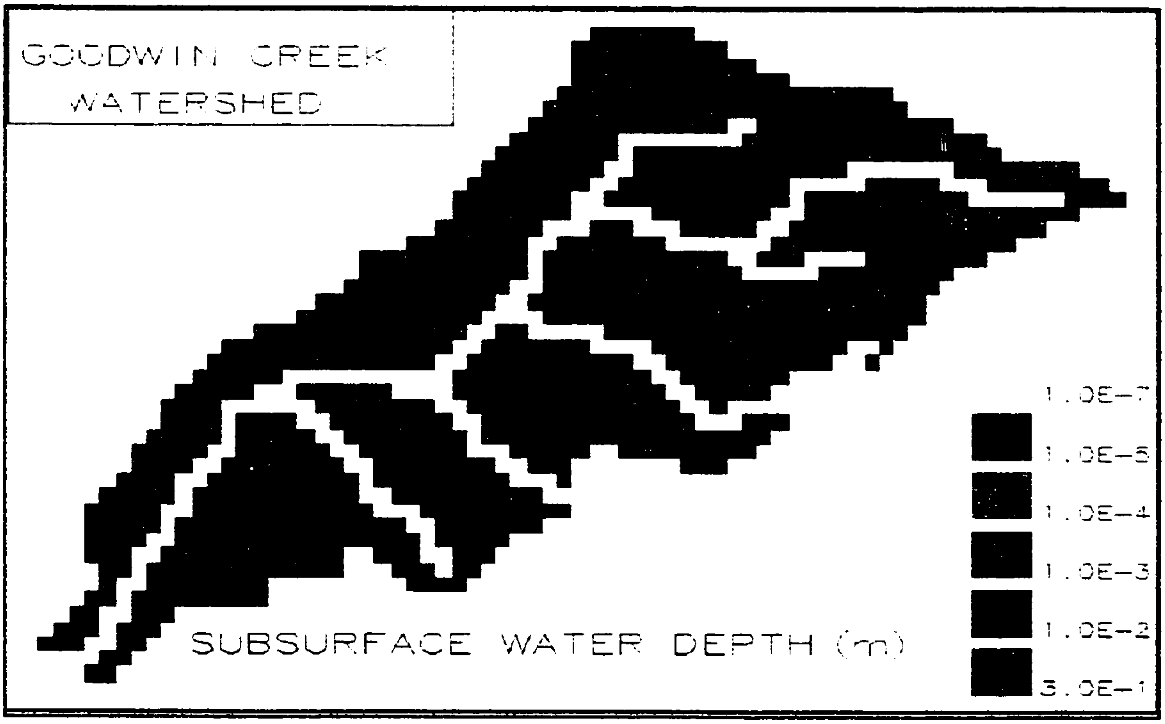


Figure 4.11b: Subsurface flow representation at 50 minutes

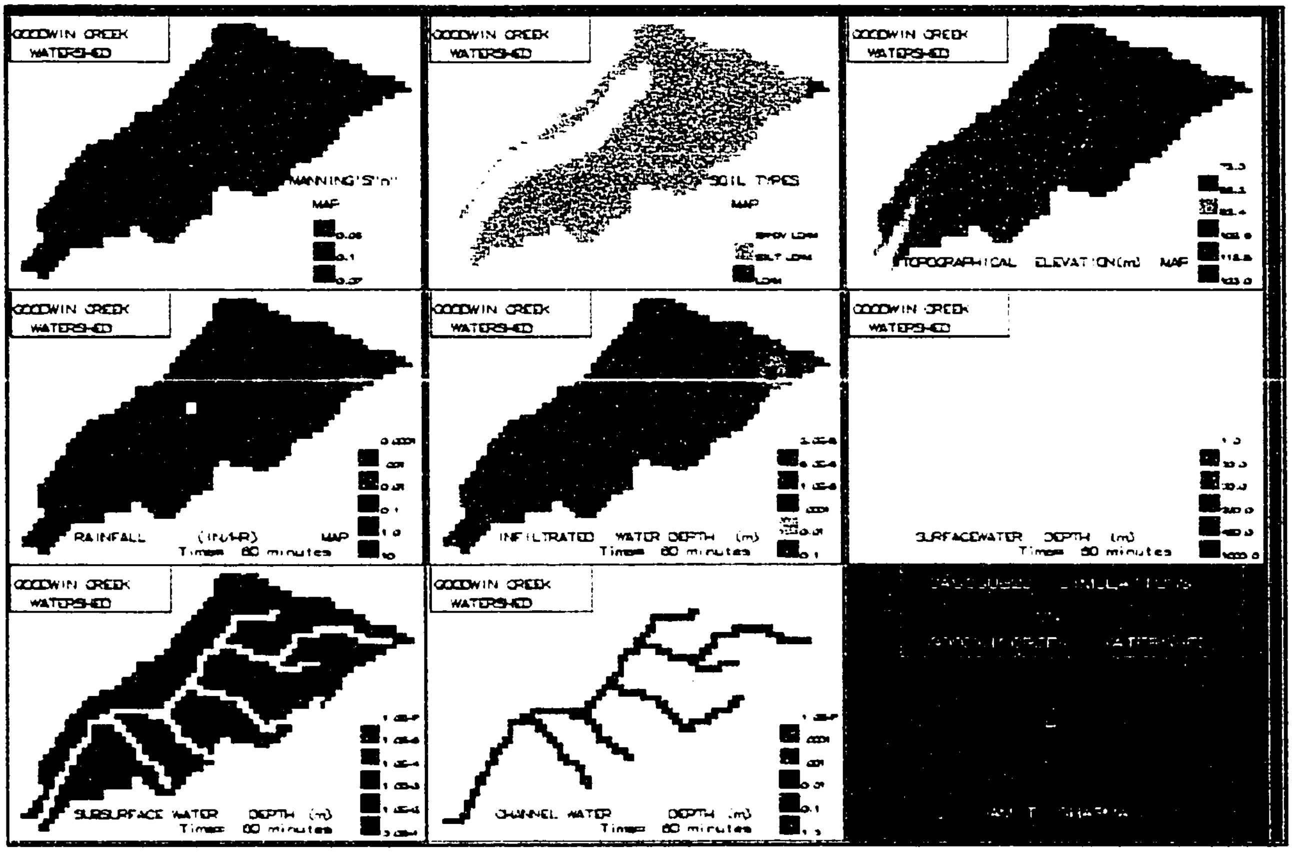


Figure 4.12a: Graphic representation of continuous simulation frame at 60 minutes

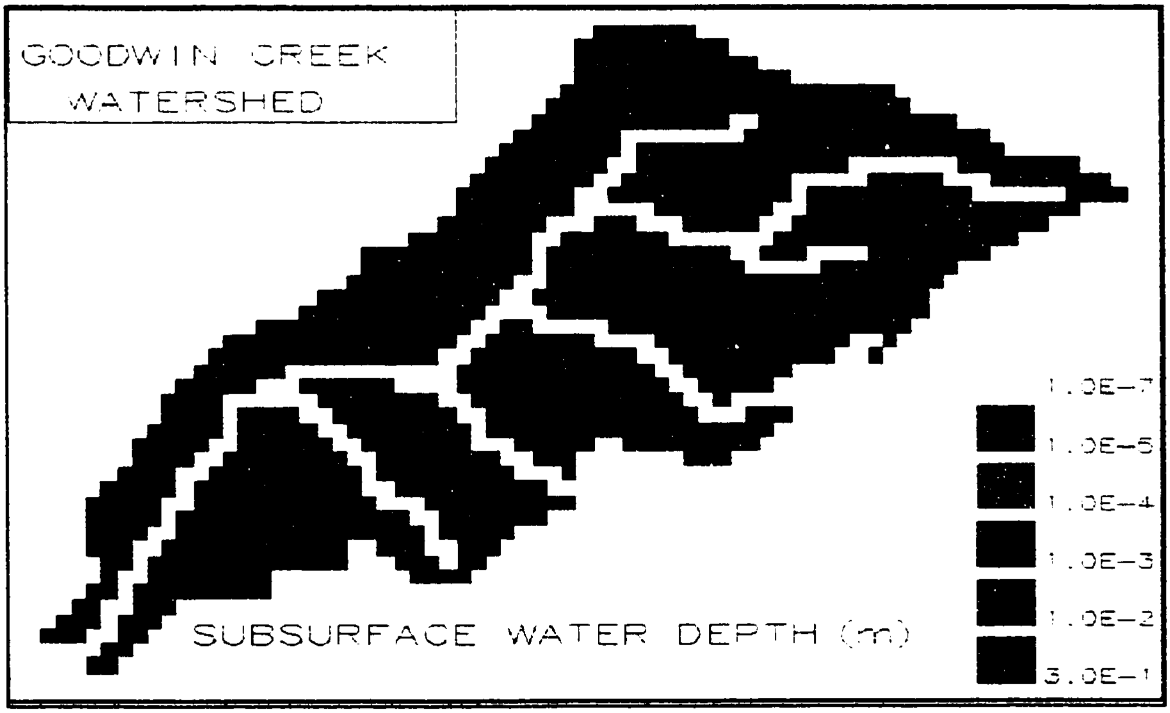


Figure 4.12b: Subsurface flow representation at 60 minutes

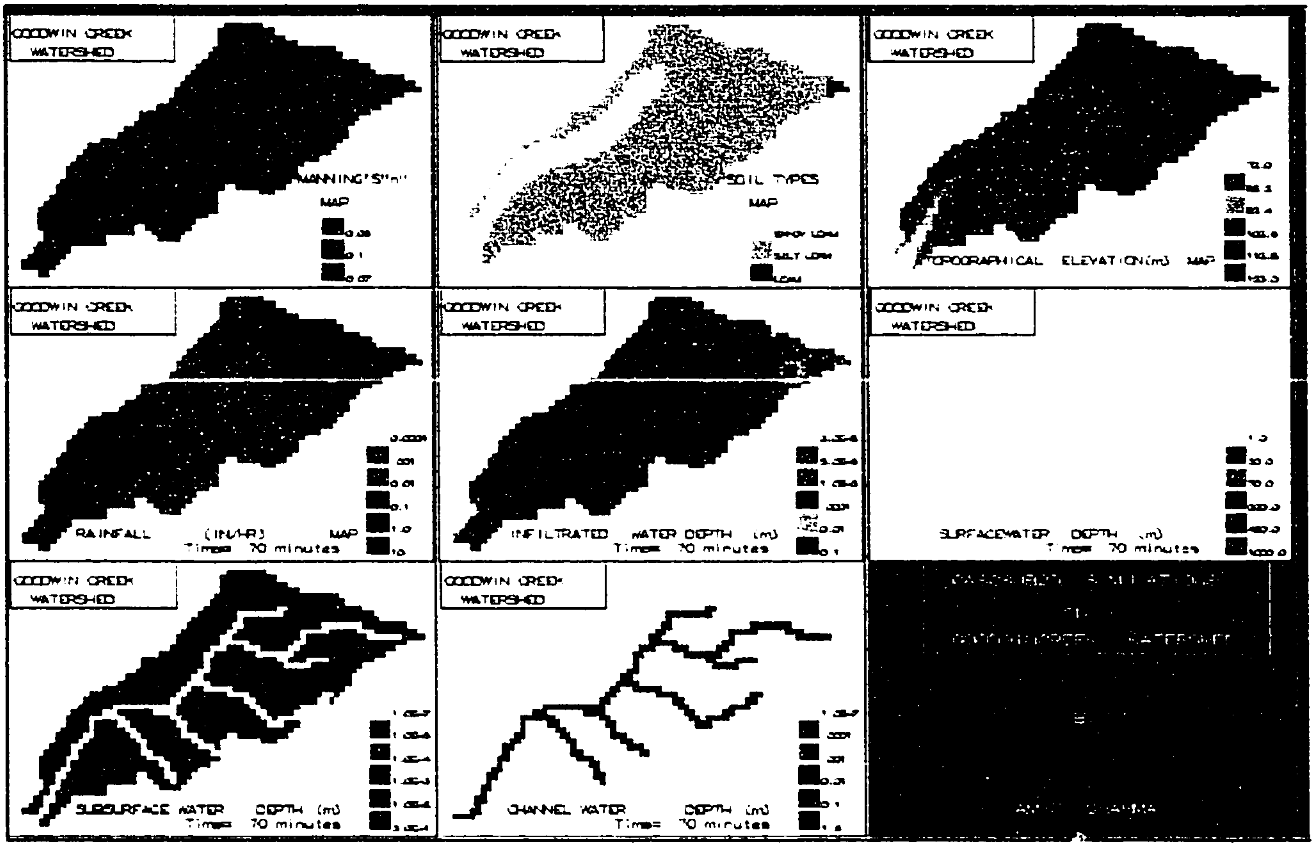


Figure 4.13a:Graphic representation of continuous simulation frame at 70 minutes

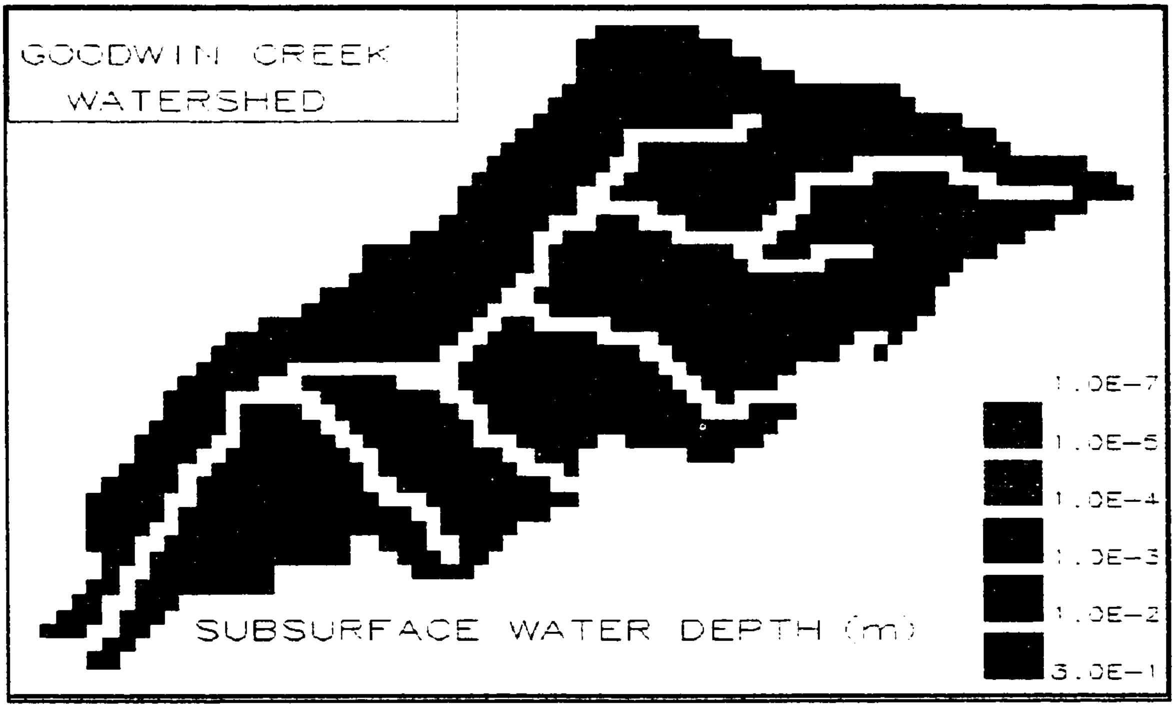


Figure 4.13b: Subsurface flow representation at 70 minutes

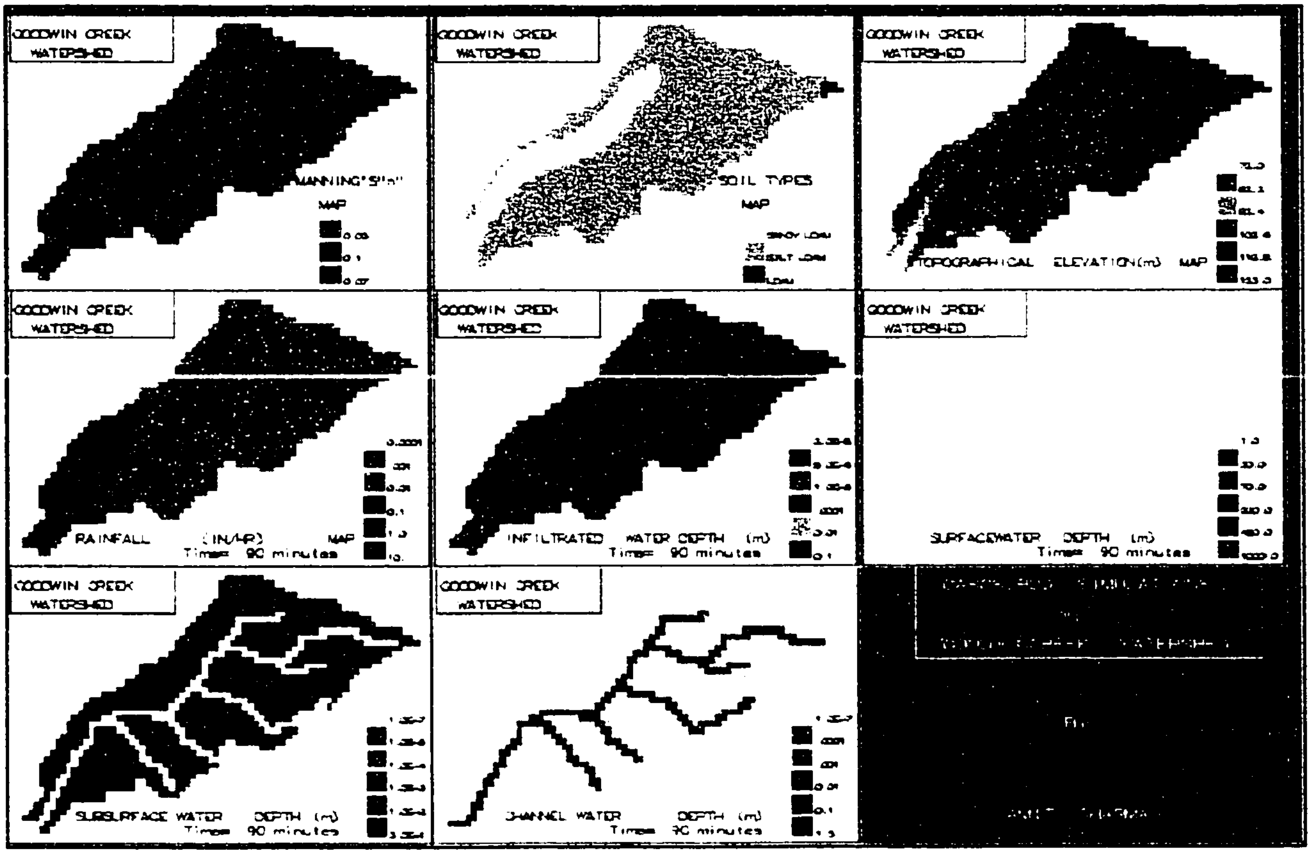


Figure 4.14a: Graphic representation of continuous simulation frame at 90 minutes

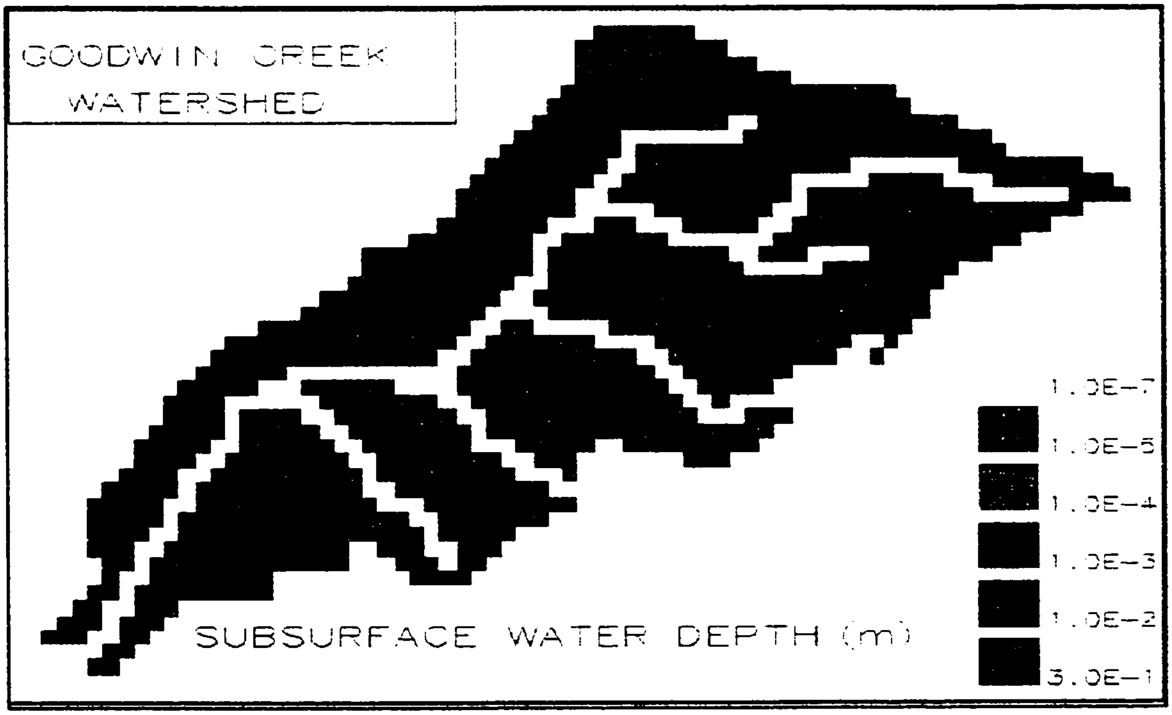


Figure 4.14b: Subsurface flow representation at 90 minutes

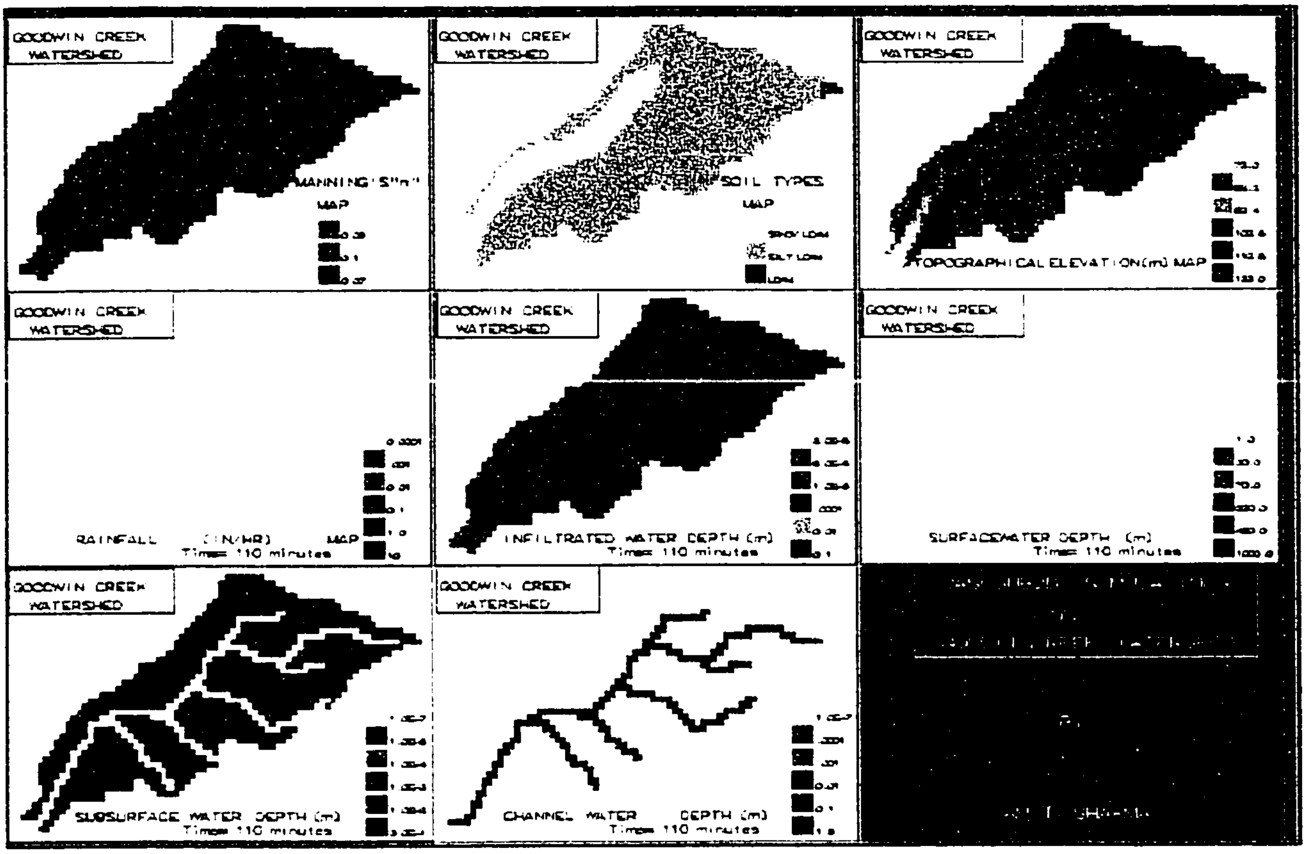


Figure 4.15a: Graphic representation of continuous simulation frame at 110 minutes

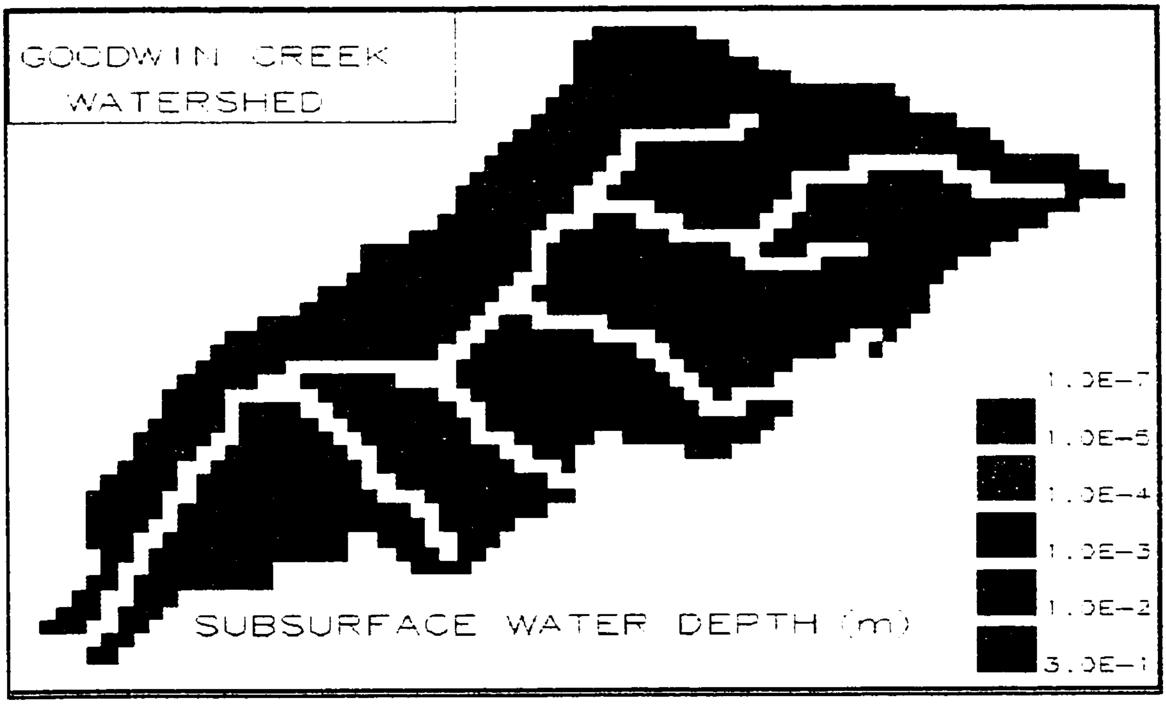


Figure 4.15b: Subsurface flow representation at 110 minutes

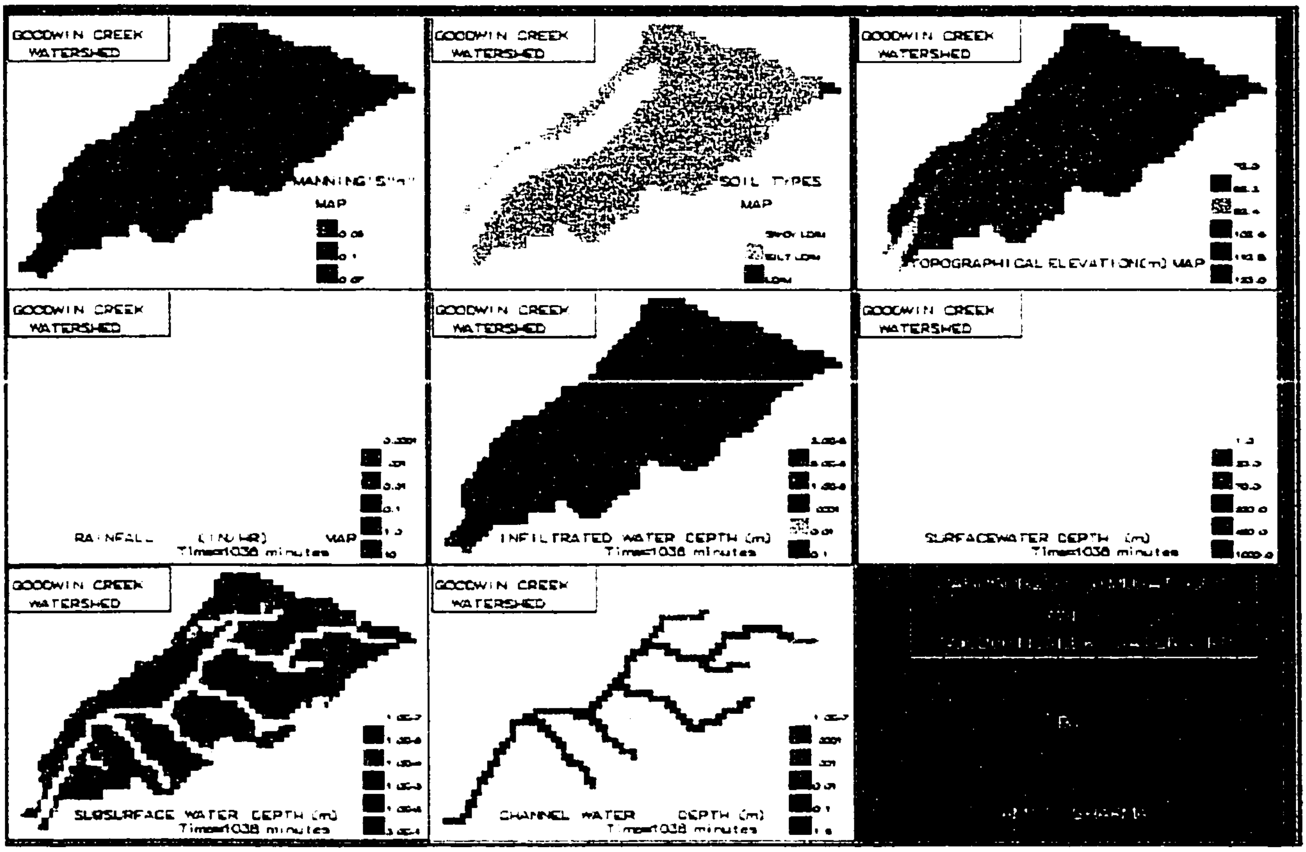


Figure 4.16a: Graphic representation of continuous simulation frame at 1036 minutes

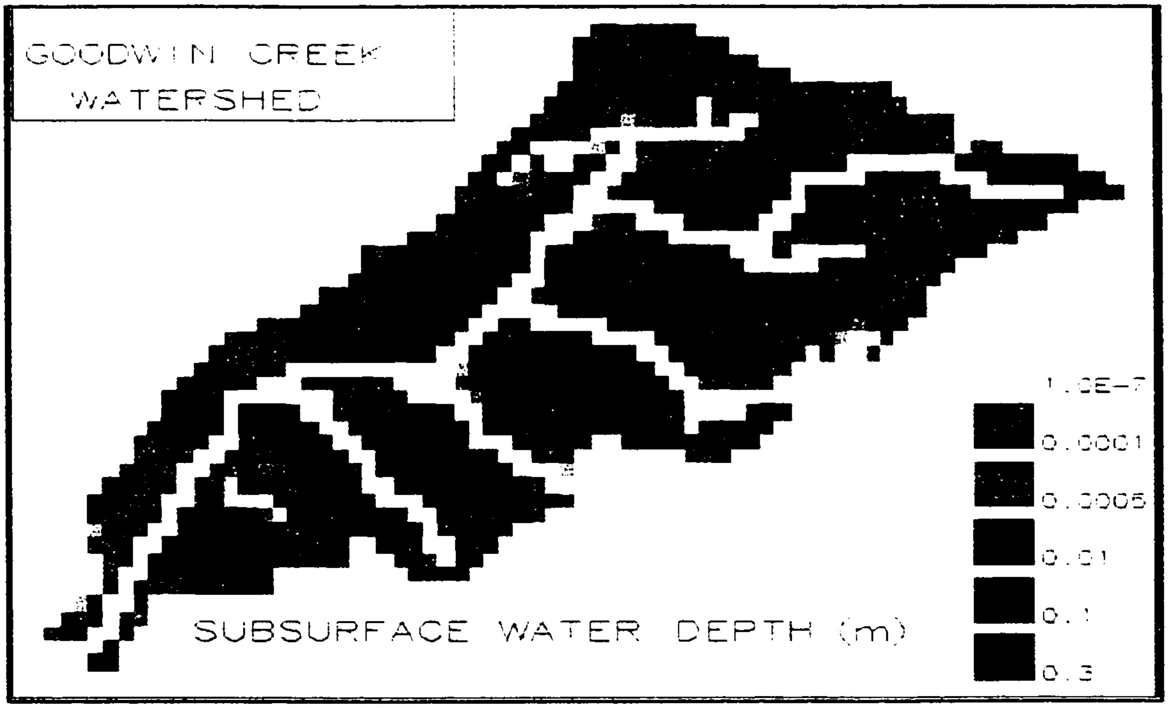


Figure 4.16b: Subsurface flow representation at 1036 minutes

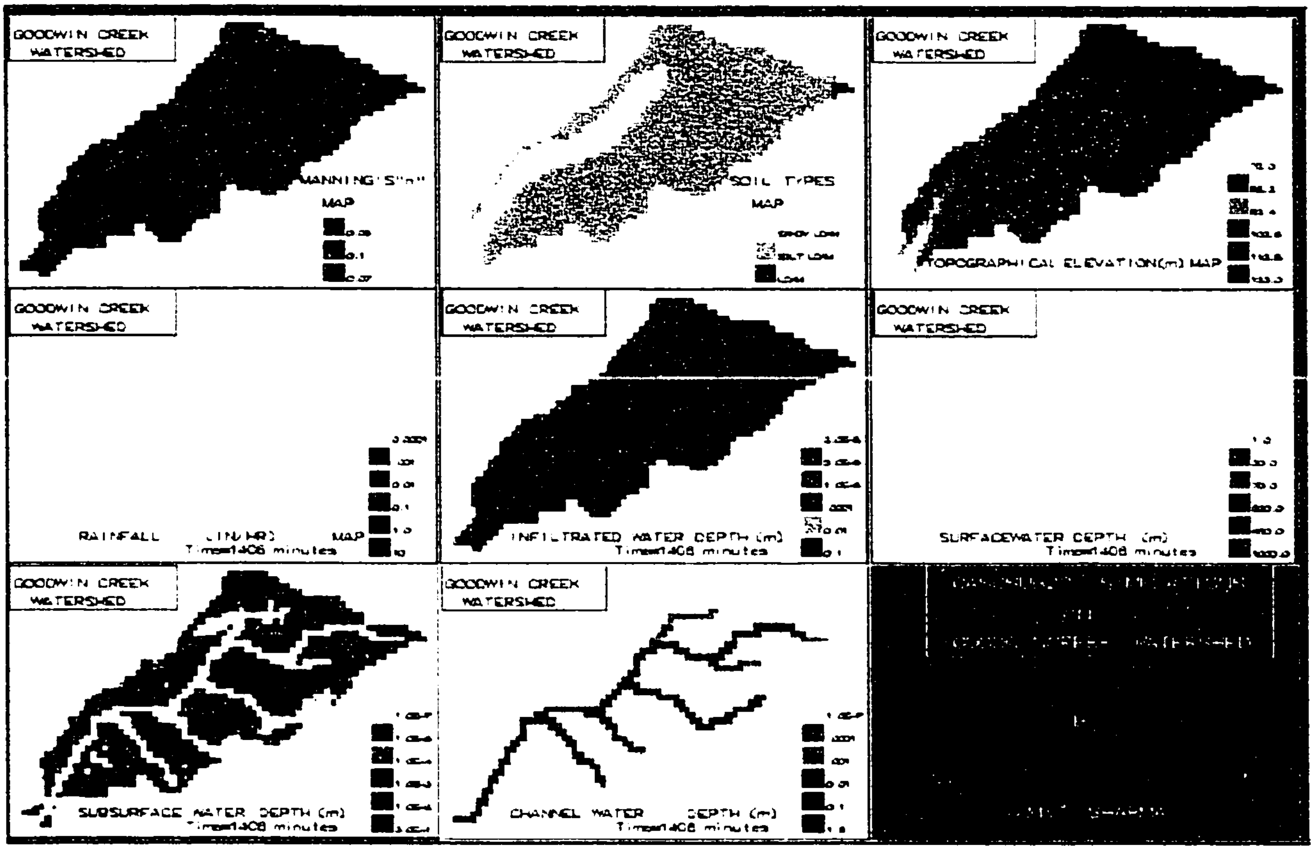


Figure 4.17a: Graphic representation of continuous simulation frame at 1406 minutes

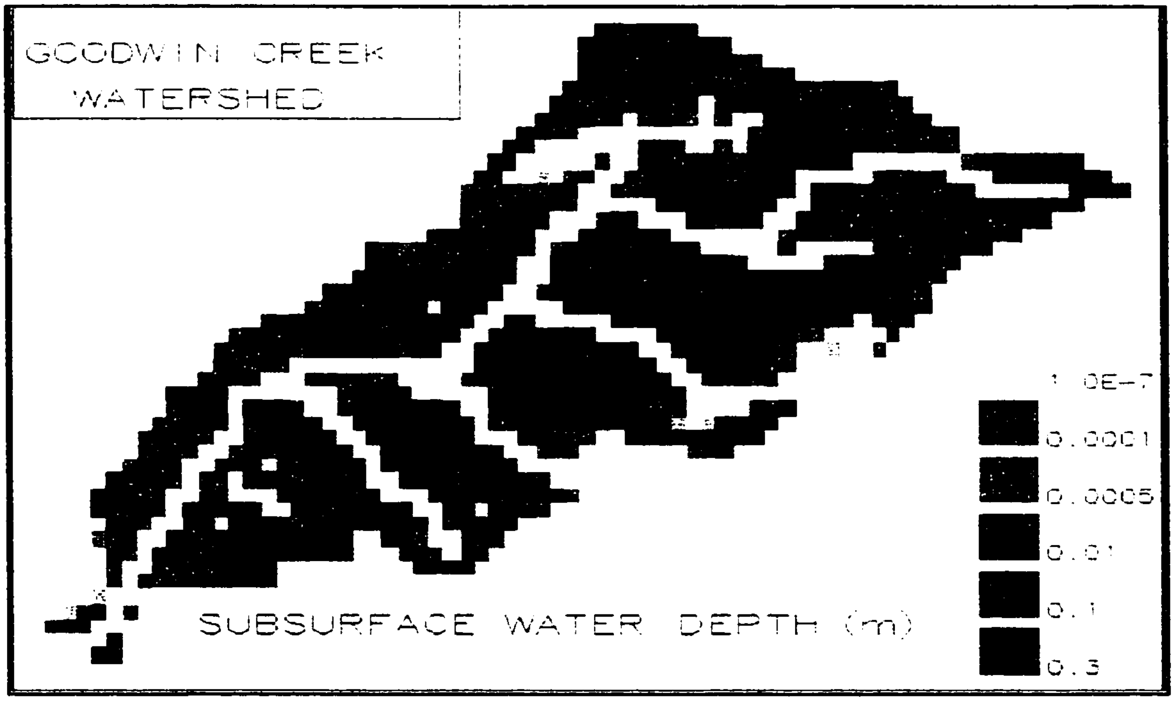


Figure 4.17b: Subsurface flow representation at 1406 minutes

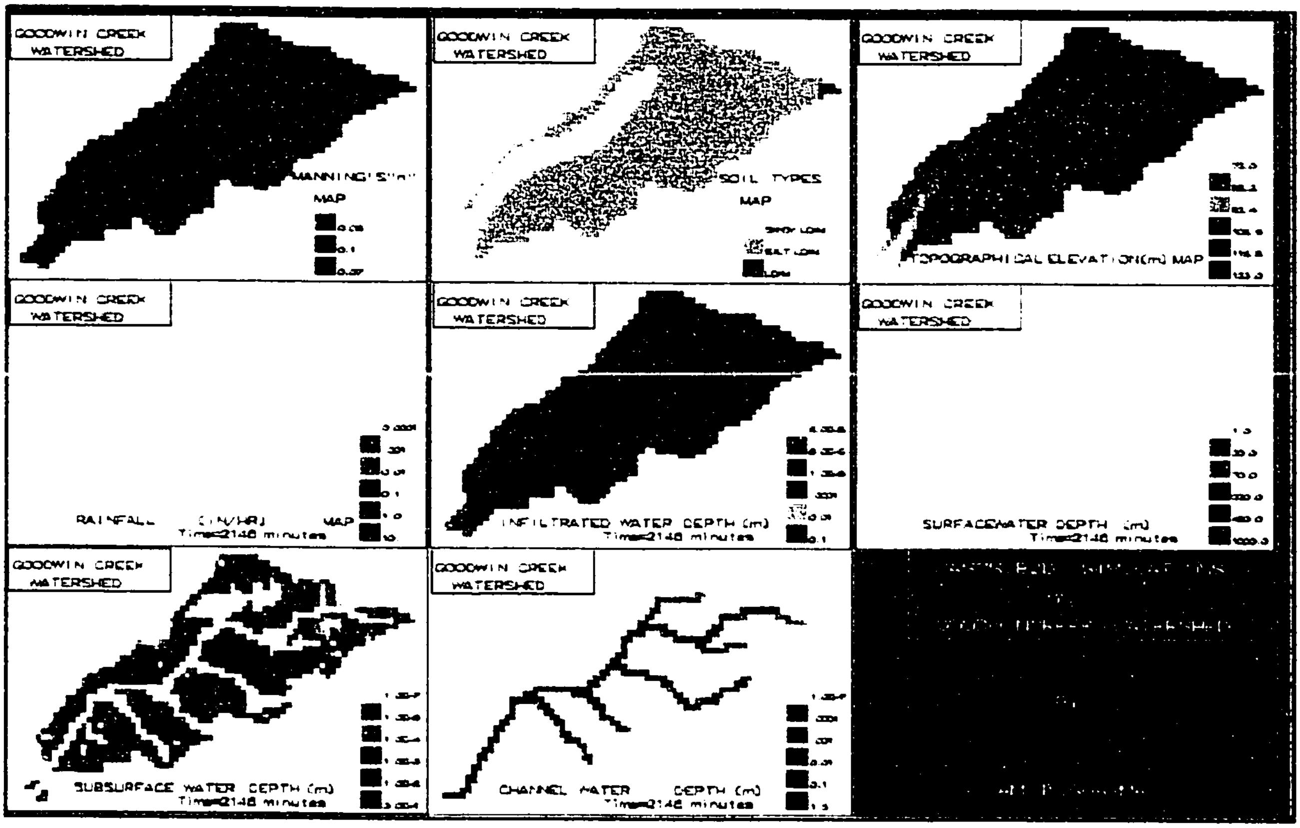


Figure 4.18a: Graphic representation of continuous simulation frame at 2146 minutes

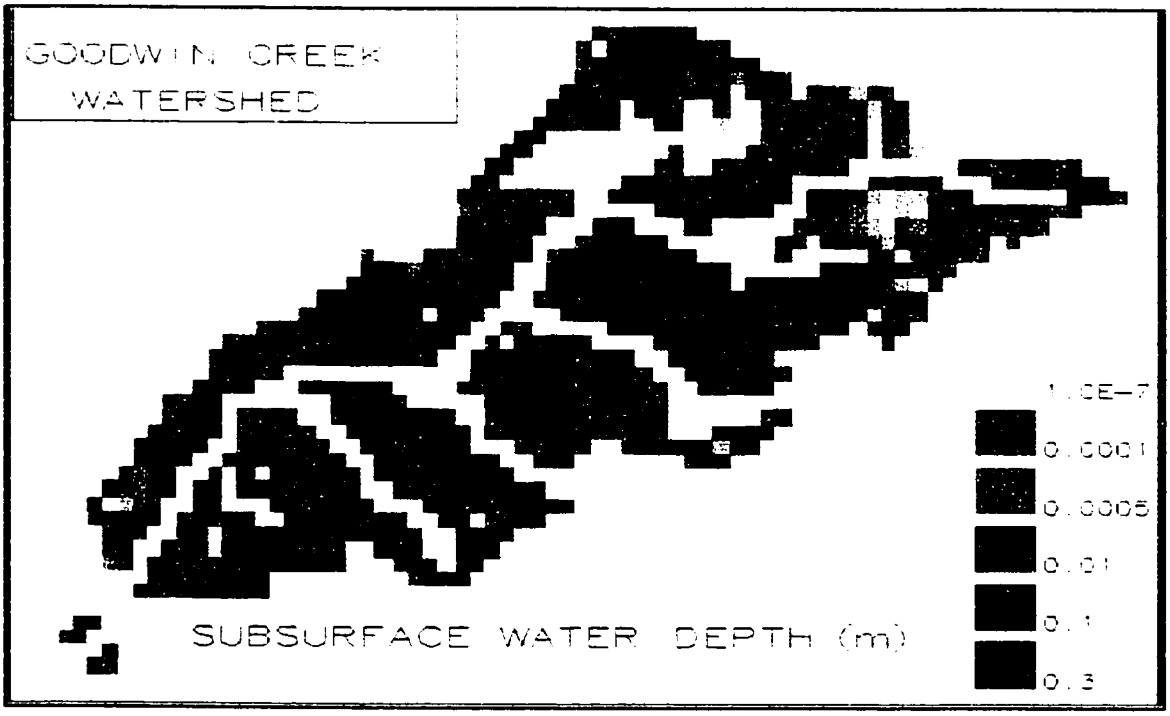


Figure 4.18b: Subsurface flow representation at 2146 minutes

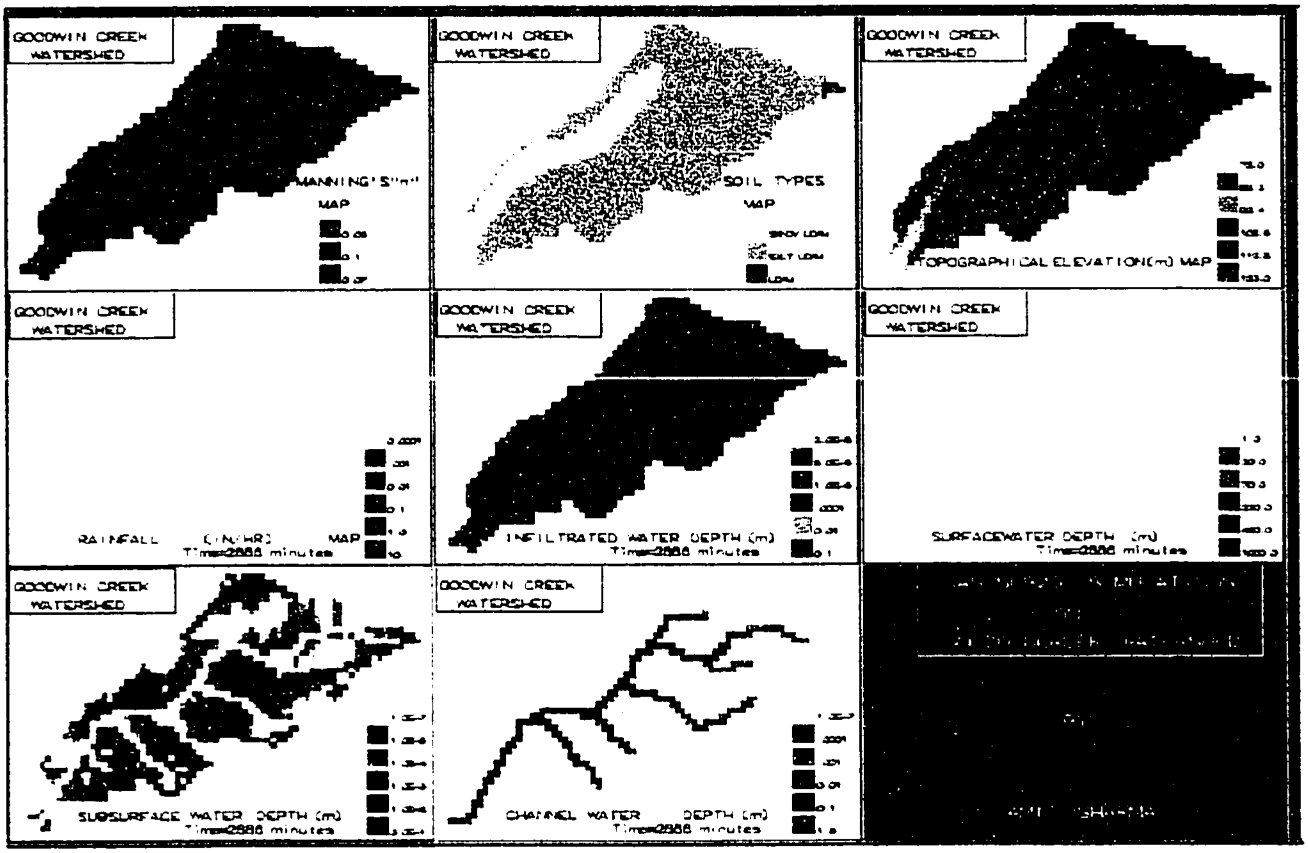


Figure 4.19a: Graphic representation of continuous simulation frame at 2866 minutes

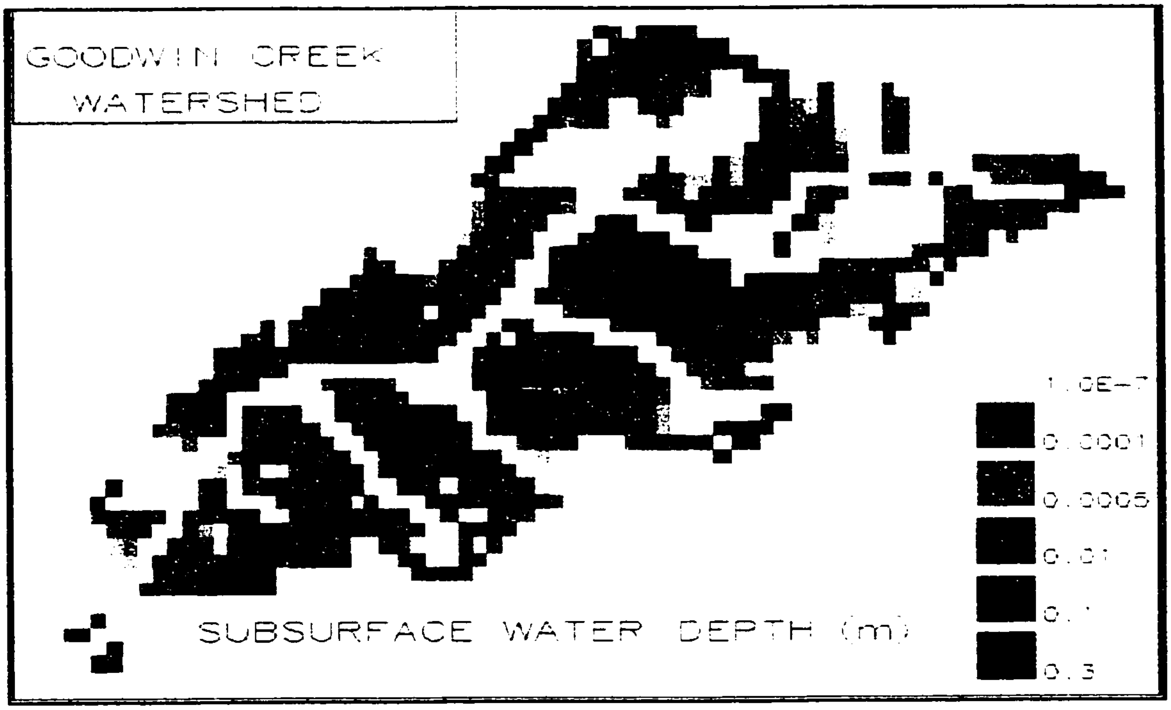


Figure 4.19b: Subsurface flow representation at 2866 minutes

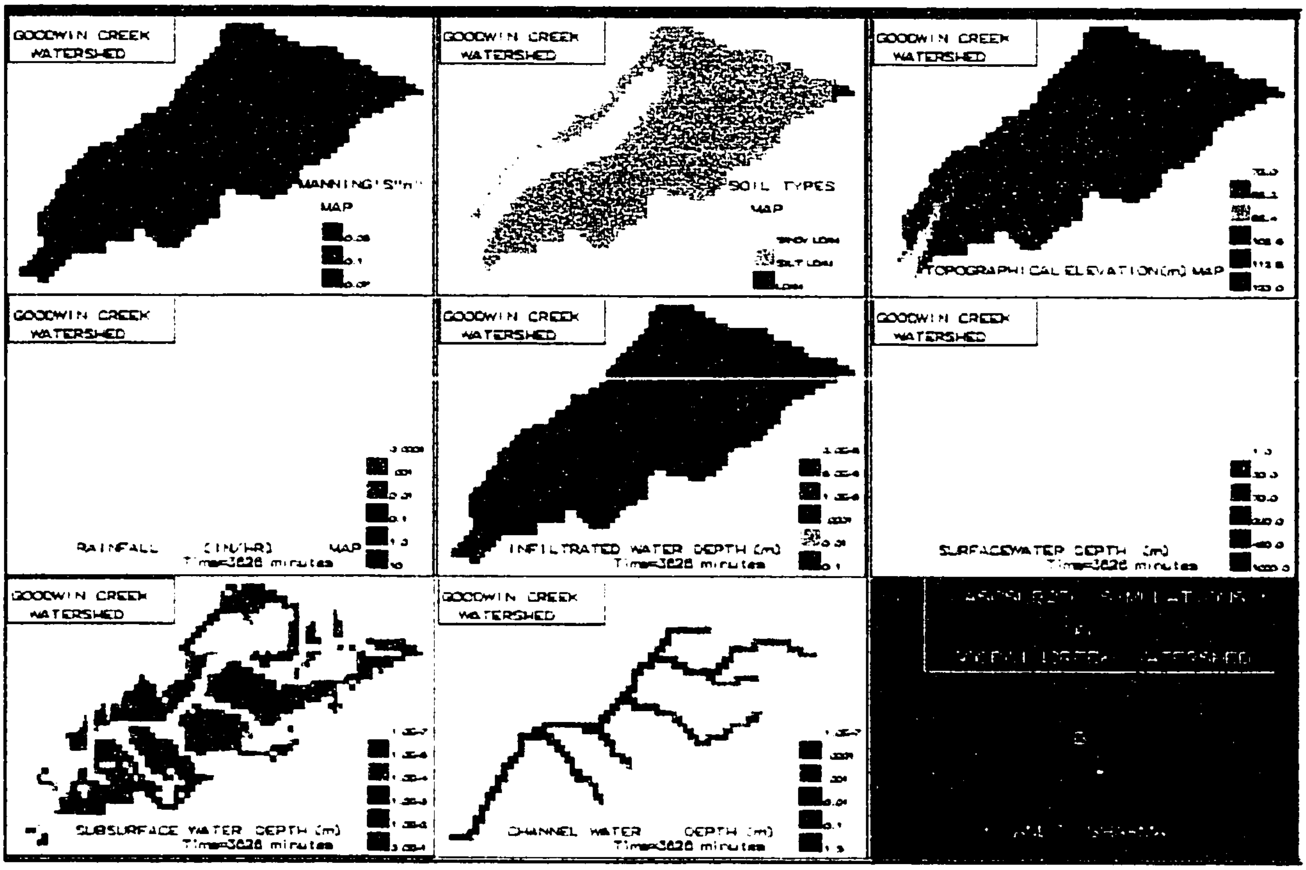


Figure 4.20a: Graphic representation of continuous simulation frame at 3828 minutes

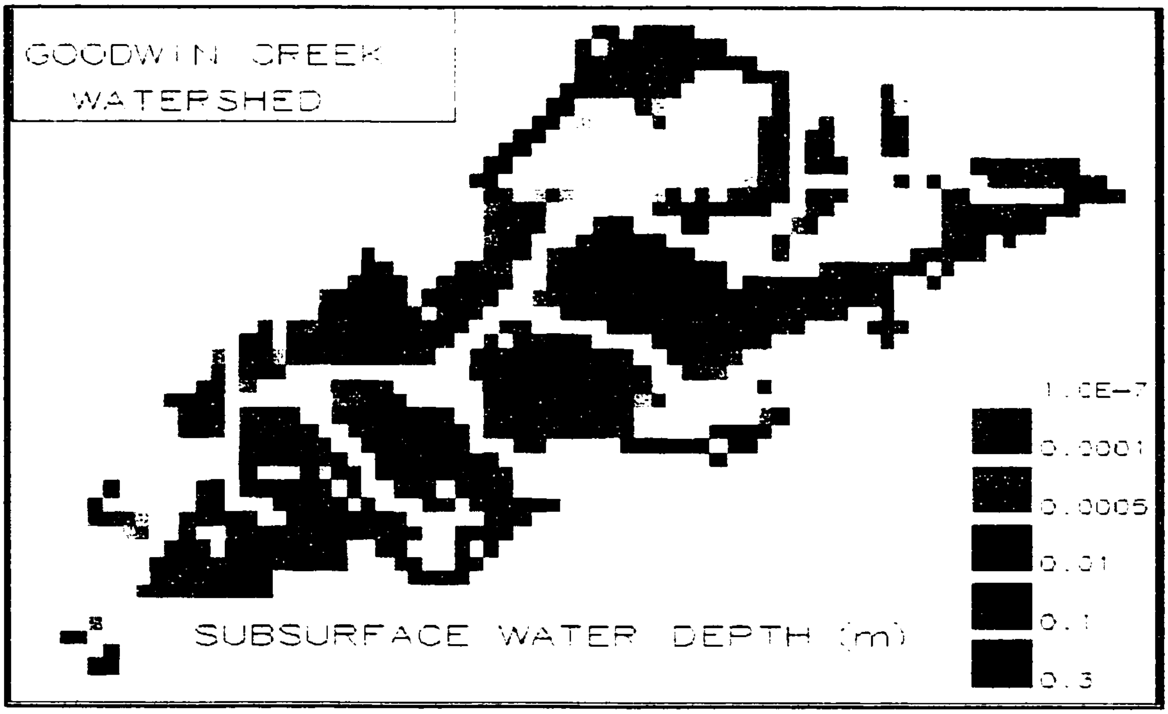


Figure 4.20b: Subsurface flow representation at 3828 minutes

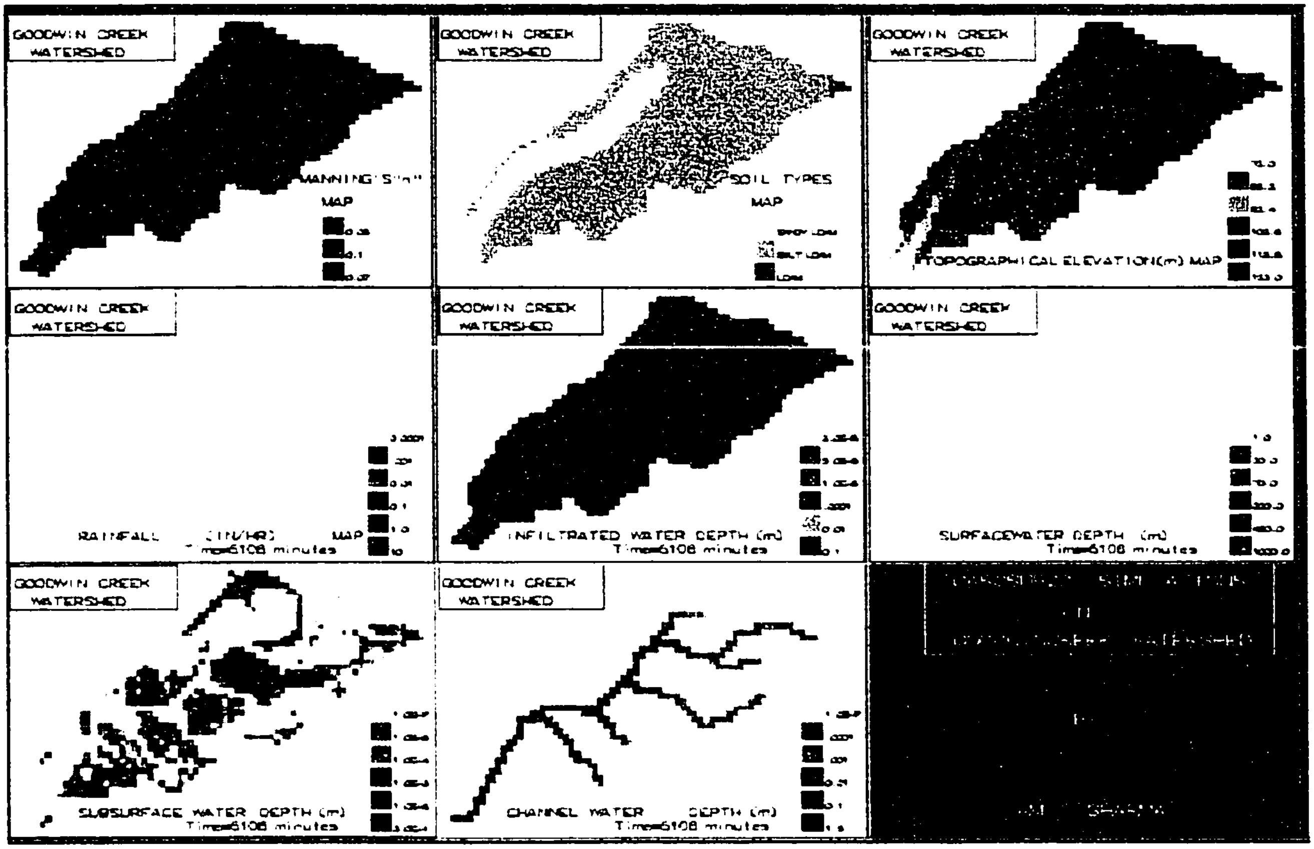


Figure 4.21a: Graphic representation of continuous simulation frame at 5106 minutes

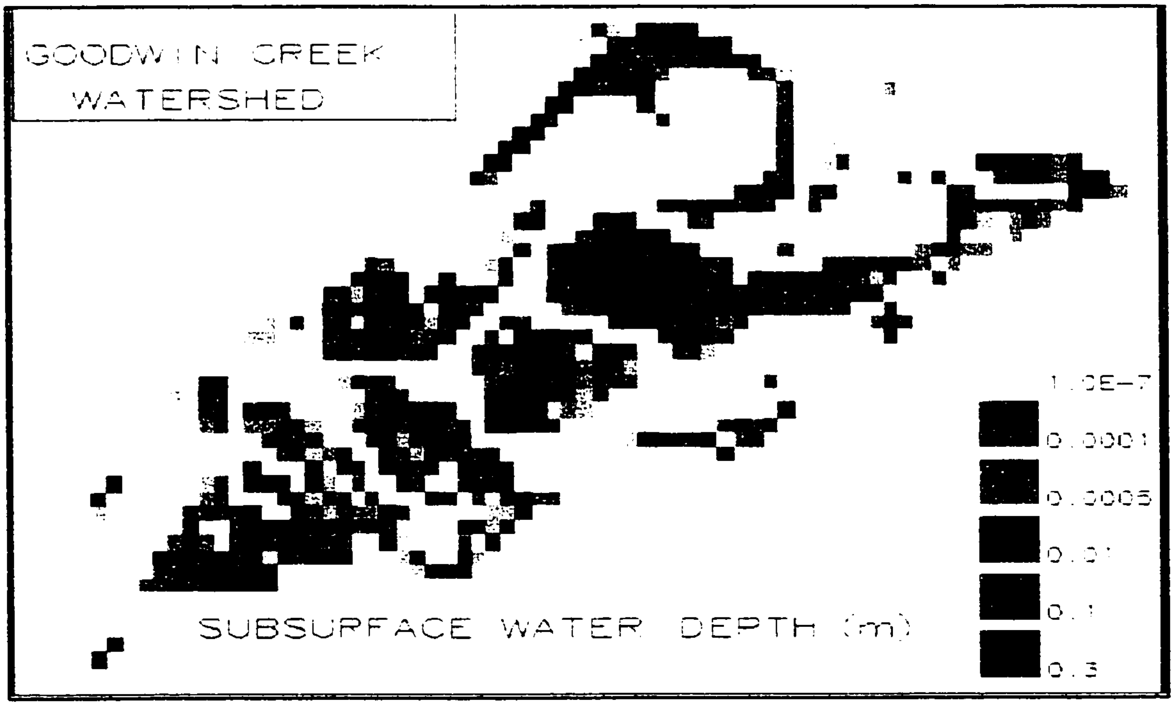


Figure 4.21b: Subsurface flow representation at 5106 minutes

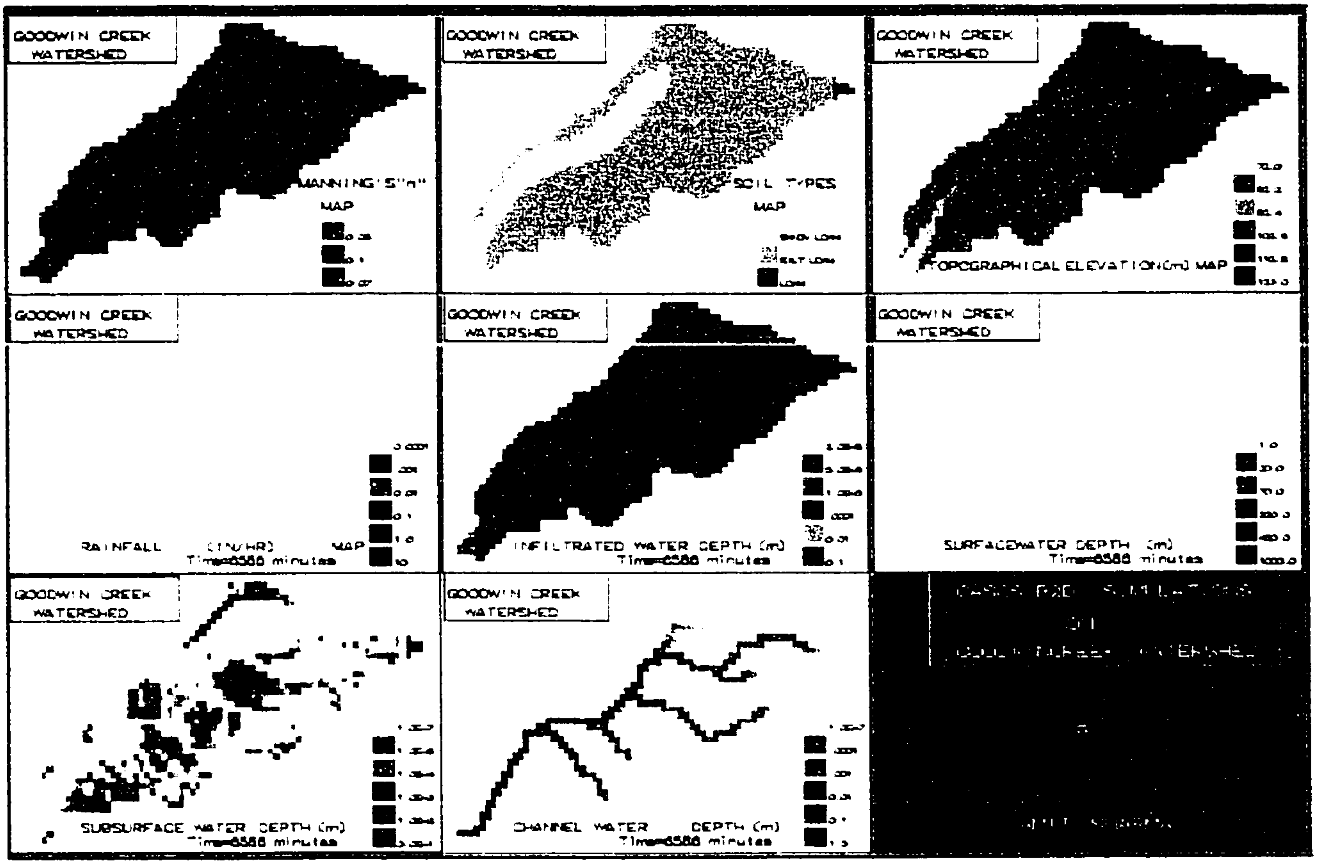


Figure 4.22a: Graphic representation of continuous simulation frame at 6536 minutes

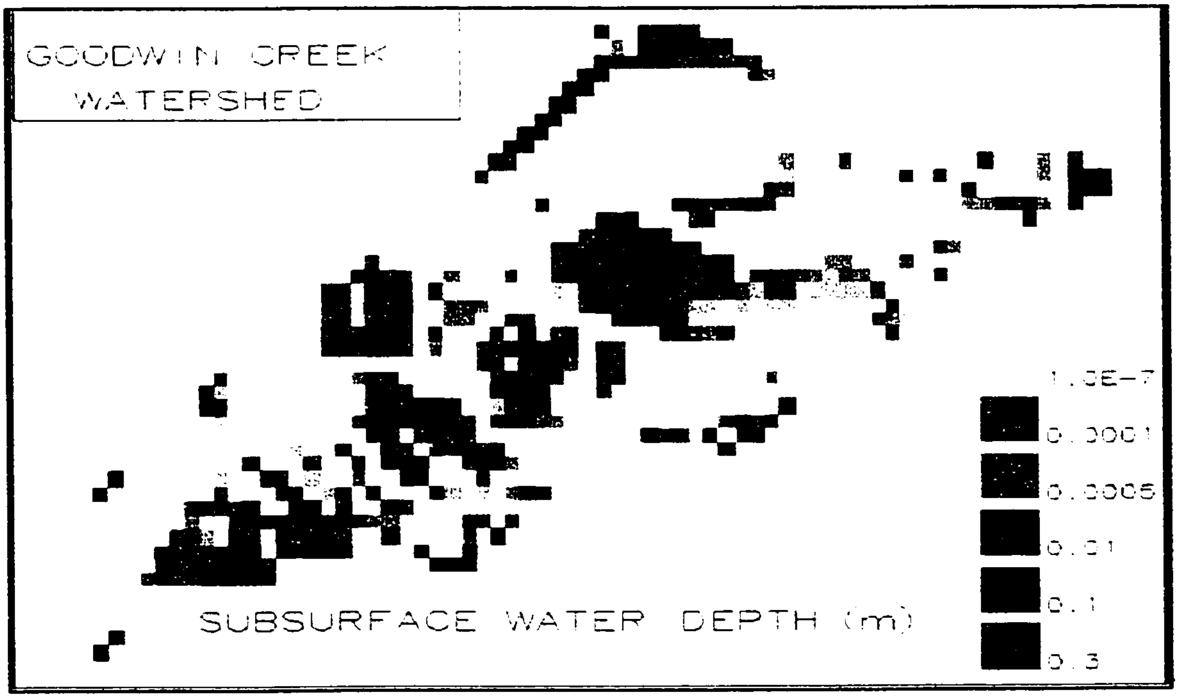


Figure 4.22b: Subsurface flow representation at 6536 minutes

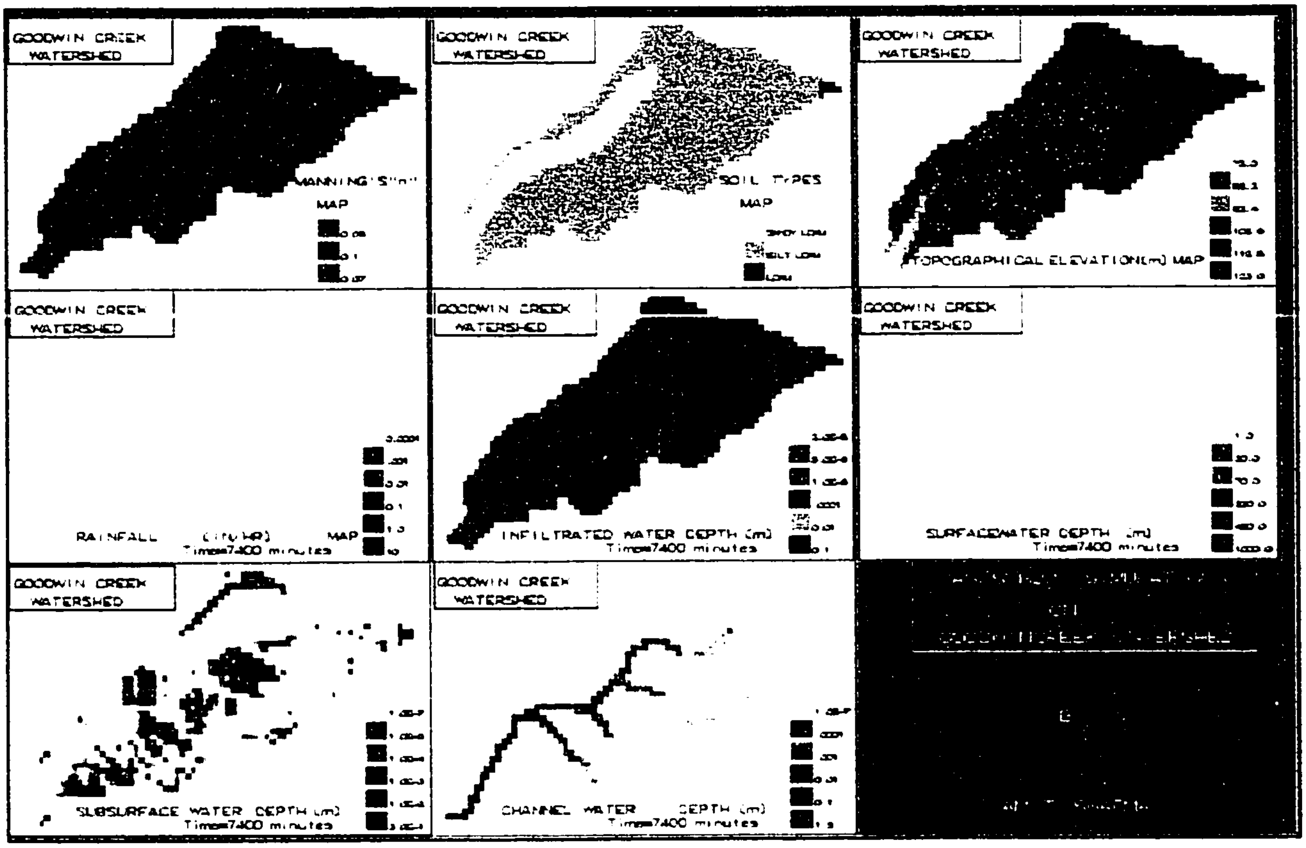


Figure 4.23a: Graphic representation of continuous simulation frame at 7400 minutes

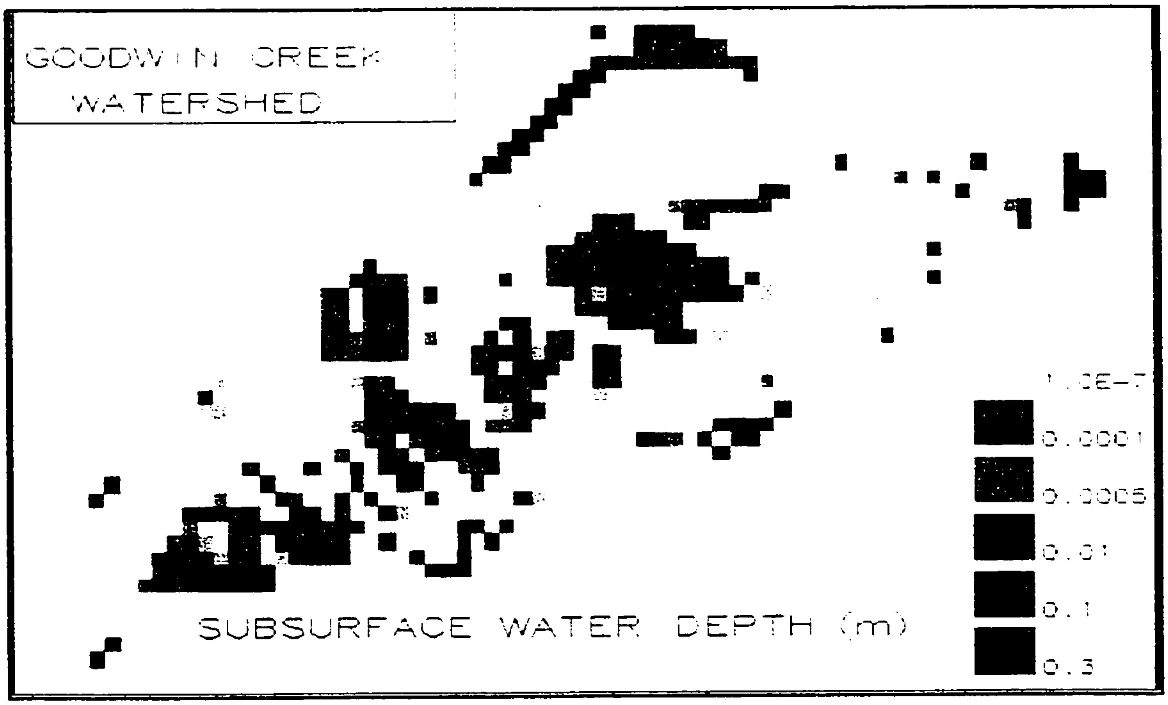


Figure 4.23b: Subsurface flow representation at 7400 minutes

4.4 MODEL VERIFICATION

The calibrated model was verified using an independent set of rainfall-runoff data generated by the storm event of December 2 and 3, 1983. The storm event of December 2, 1983 began at 12:00 am, and lasted for 30 hours. The total average rainfall was 5.82 inches. Fig.4.26 shows the rainfall event and Fig. 4.27 shows the simulated and the observed hydrograph for the event.

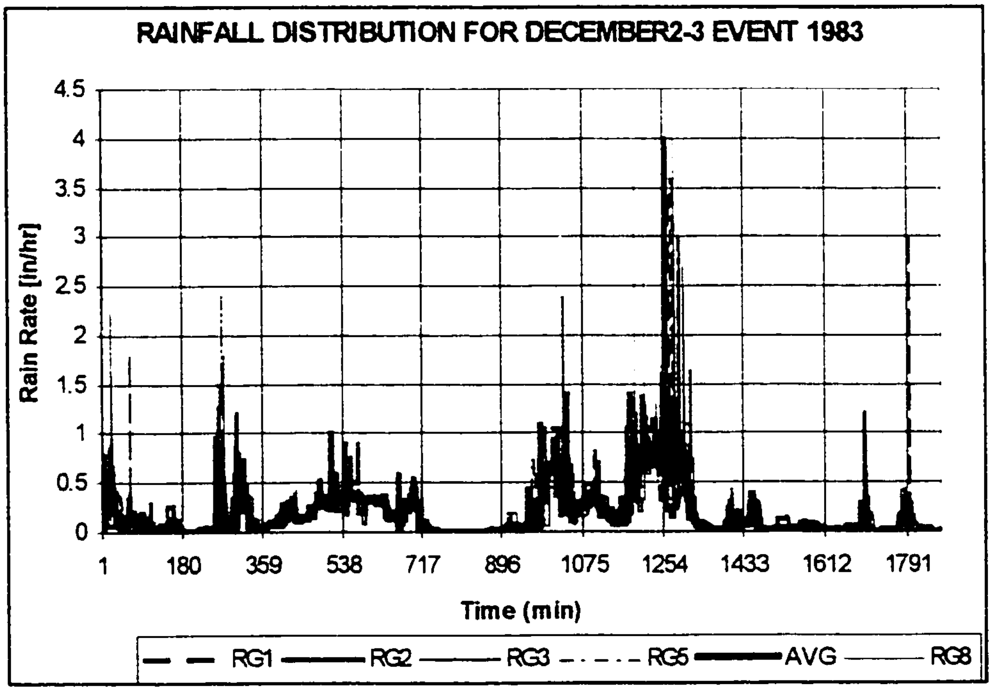


Figure 4.25: Graphic representation of rainfall distribution of Dec.2

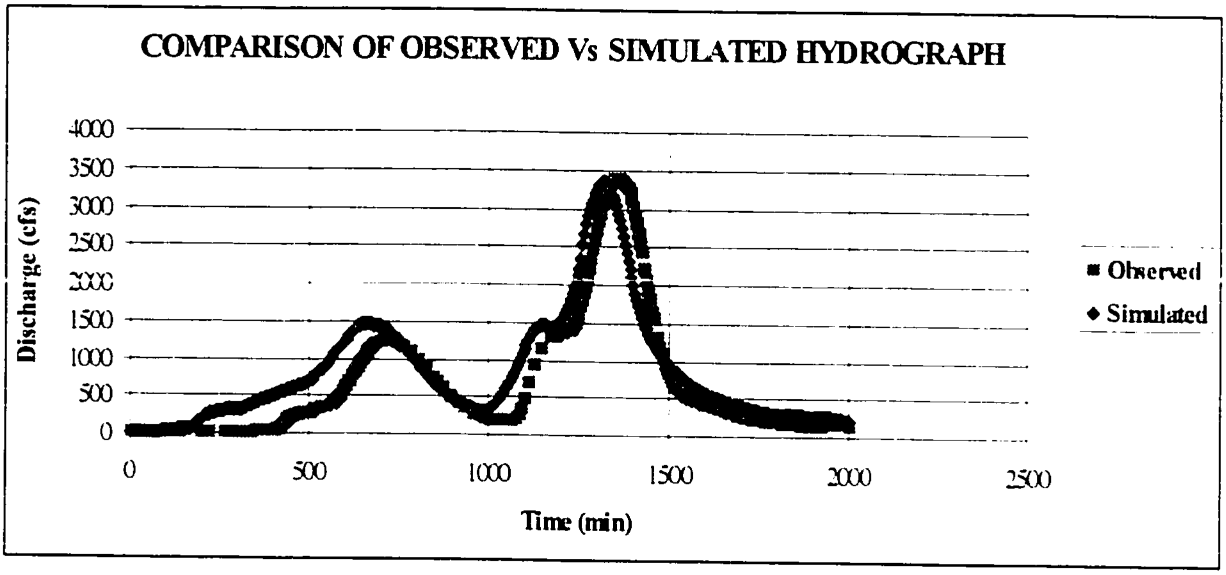


Figure 4.26: Comparison of Hydrographs for Dec.2 event

The simulated hydrograph follows the same trend as the observed hydrograph, but the first peak for the simulated hydrograph is higher, with 1466cfs at 665 minutes, while the observed peak is 1251cfs at 728 minutes, suggesting that the simulated peak comes one hour earlier than the observed peak. However, the major peak for the simulated hydrograph is 3351cfs at 1325 minutes, and the observed peak 3373cfs at 1349 minutes is only 24 minutes apart. It is inferred that the simulated hydrograph matches the observed hydrograph trend, indicating that the model is aptly capable of simulating the real processes.

Thus, the model CASC2DSUB was calibrated on the short duration (3.15hrs) rainstorm event of October 17, 1981, and verified on a long-duration (30hrs) rainstorm event of December 2, 1983. The process of graphic visualization was achieved through the graph.f program operating in the GRASS environment, with input files for the generation of the color schemes and legends.

CHAPTER V

CONDITIONS OF SUBSURFACE CONTRIBUTION

The CASCSUB2D model was simulated on the Goodwin Creek watershed for various ranges of parameter values to ascertain and quantify the conditions under which the subsurface flow is the major contributor to the watershed response. The first condition for the subsurface to be effective at all is the hydraulic conductivity of the soil. A soil with a high hydraulic conductivity such as gravel is a good example, where most of the rainwater infiltrates into the soil matrix, subsequently generating lateral flow to the channels, and finally flowing towards the outlet of the watershed. Thus the hydrograph generated at the outlet is mainly the product of the subsurface water. This is observed in Fig.3.9

5.1 DIMENSIONAL ANALYSIS

A dimensional analysis was done to infer the influence of subsurface on the watershed response based on the intensity of the rainfall event and the soil type. This was achieved by the determination of a dimensionless parameter, the value of which would be indicative of subsurface involvement to the watershed response.

A variable, rainfall intensity was applied to the watershed with a uniform soil type. In the first instance, a clay soil type with a hydraulic conductivity of 8.33E-08m/s was used with a rainfall intensity that varied from 8.33E-05m/s to 1.04E-04m/s. Later, a silt soil type was selected with hydraulic conductivity of 1.81E-06m/s and was modeled with a rainfall intensity that varied from 3.62E-06m/s to 6.03E-07m/s. Finally, the CASCSUB2D model was simulated for the soil type sand with hydraulic conductivity of 3.27E-05m/s and the model simulated a rainfall intensity that varied from 4.09E-05m/s to 1.09E-05m/s. Clay and sand were selected as the two extremities of the soil type, with clay having the lowest hydraulic conductivity, and sand having the highest hydraulic conductivity. Silt was selected as the intermediate soil type between the two extremities. In addition to these simulations, additional simulations were conducted for soil types silty-clay (hydraulic conductivity = 1.39E-7m/s), silty-clay-loam (hydraulic conductivity = 2.78E-7m/s), loam (hydraulic conductivity = 9.44E-7m/s), and loamy-sand (hydraulic conductivity = 8.31E-6m/s).

A dimensionless analysis was conducted by plotting data generated from each of the runs. The y ordinate of the graph is given as the ratio of the total subsurface volume to the total volume of the water flowing out of the watershed. The x ordinate is defined as the ratio of the hydraulic conductivity (k) to the rainfall intensity (i). In other words the dimensionless hydrograph has an axis system of Subsurface volume of water /Total volume of water versus k/i. It is observed from Figure 5.1 that the hydrograph for the soil type clay starts at a k/i value of 0, while the hydrograph for the soil type silt starts at a k/i value of 0.25, and the hydrograph for soil type sand starts at a k/i value of 0.78. This is in accordance with the increasing hydraulic conductivities of the soil samples applied to the watershed.

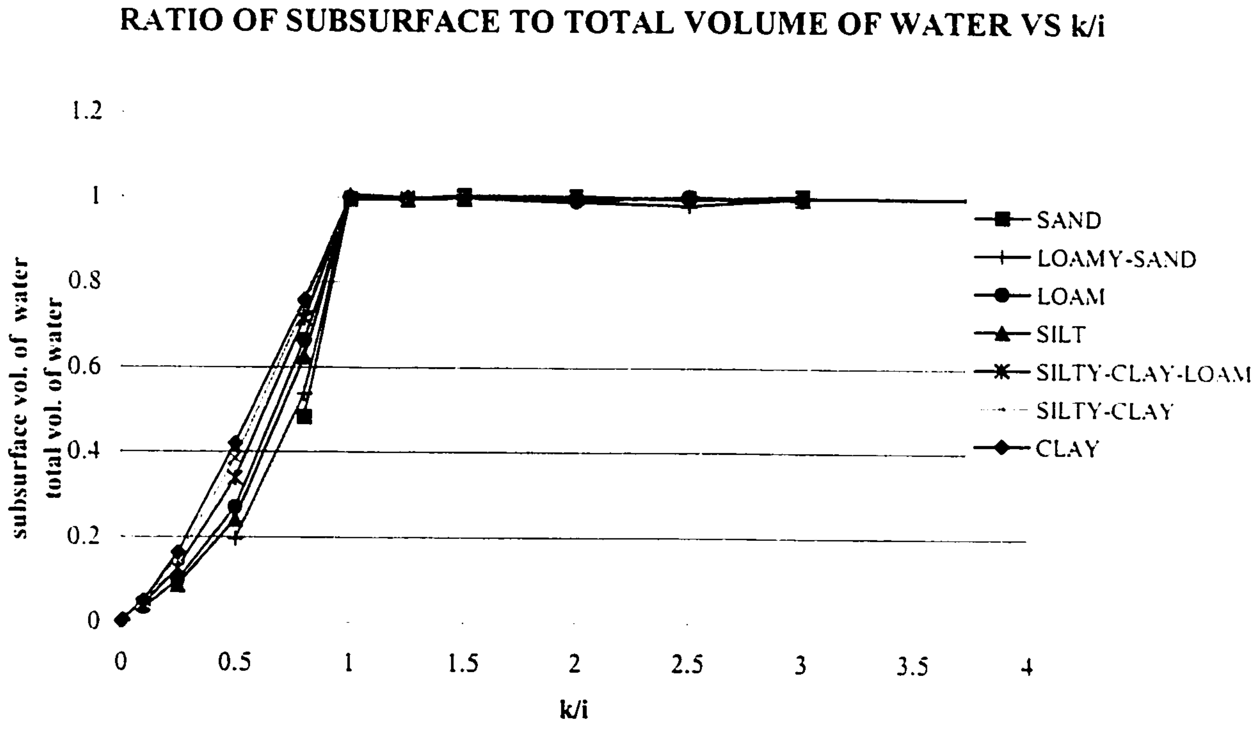
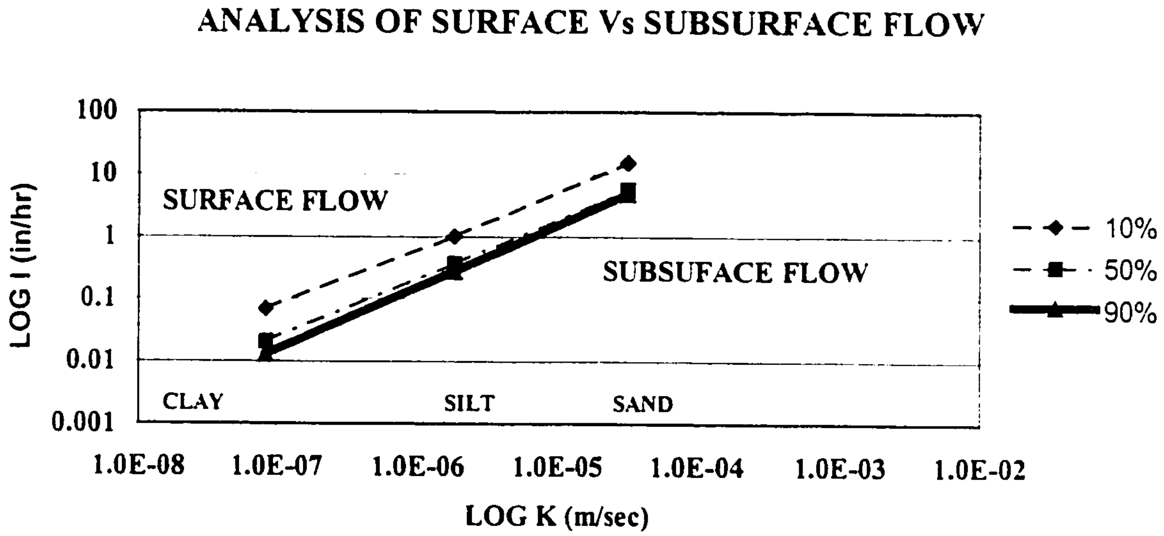


Figure 5.1: Ratio of subsurface to total volume of water vs k/i for various soils

Also it is observed that at a k/i ratio of 1 and greater, the maximum ratio of Subsurface volume of water /Total volume of water is reached for each of the soil types.

From Figure 5.1, surface versus subsurface flow is analysed. This is observed in Figure 5.2 where 10%, 50%, and 90% projections are made for rainfall intensity (i) versus hydraulic conductivity (K). Figure 5.2 has a wide applicability, such that inferences can be made about the surface flow or the subsurface flow influence based on the watershed soil type and the rainfall intensity of the storm event.



For example, let there be a watershed with a soil type that is a combination of clay and silt, which implies that the hydraulic conductivity of the soil lies in the range of 1E-07m/s to 1E-06m/s, and let the rainfall intensity be on the order of 1in/hr. Then from Figure 5.2, it can be easily inferred that surface flow will be the dominating physical process for such a watershed. However, if the soil type is a combination of silt and sand, with hydraulic conductivities lying between 1E-06m/s to 1E-03m/s, and the rainfall intensity is of the order of 0.1 in/hr, then subsurface flow would be the governing physical process influencing the watershed response.

Goodwin Creek watershed was also subjected to a uniform rainfall intensity of 1E-5m/s, having clay as a uniform soil type throughout the watershed. Most of the rainfall stays on the surface, as the hydraulic conductivity of clay is very small (8.33E-8m/s). Hence the major flow affecting the watershed response is mainly overland flow. Next, the watershed response is simulated for the same rainfall intensity, but with gravel as the uniform soil type. Gravel has a high hydraulic conductivity (3.28E-2m/s) as compared to clay. Hence, most of the water infiltrates into the soil, and subsequently flows into the channels. The subsurface water retention is inconsequential. However, if the system is simulated for sand as the uniform soil type overlaying the watershed, then even with considerable infiltration, there is not much flow to the channels. Thus, the major portion of subsurface water is retained in the soil matrix, and the outflow from the watershed is considerably reduced.

CHAPTER VI

SUMMARY AND CONCLUSIONS

The aim of this research was to formulate and test a subsurface flow routine SUBFLO for the surface rainfall runoff model CASC2D. This was achieved by the application of a finite difference formulation to the St. Venant equations of continuity and momentum, and Darcy's law for saturated subsurface flow. This modified model CASC2DSUB was used to study the rainfall runoff response of a watershed from rainstorm events on both a test plot and a natural watershed.

The model was calibrated and verified on the Goodwin Creek watershed for two rainstorm events on October 17-18, 1981, and December 2-3, 1983. The graphic visualization was developed in the UNIX and GRASS environments with the program graph.f listed in Appendix B. This allows continuous visualization of the ongoing hydrologic processes on the watershed. The model CASC2DSUB was used to delineate the relative influence of surface versus subsurface flow on the watershed for a wide range of soil types and rainfall intensities.

6.1 Conclusions

This research yielded the following conclusions:

The SUBFLO routine was formulated using a finite difference approximation of the St.–Venant equations of continuity and momentum in conjunction with Darcy's law for saturated subsurface flow. The modified model CASC2DSUB simulates both surface and subsurface components of rainfall runoff processes. The simulation model developed in this dissertation is fairly simple, accurate, fast, and distributed in nature.

The model incorporates 2D graphic capabilities. This allows the user to view the watershed response as simulation progresses. The graphic visualization and animation of rainfall runoff processes through GRASS was one of the highlights of the research.

The virtual test plot was subjected to varying conditions of soil types, hydraulic conductivities, and uniformly distributed rainfall intensity of 1.0E-5m/s. The results obtained for uniform clayey soils, with low hydraulic conductivity (K_s=8.33E-7m/s), show that overland flow governs the rainfall runoff process. For gravelly soils, with high hydraulic conductivity (K_s=3.0E-2m/s), all the water infiltrates into the ground, and subsurface flow is the dominant process affecting the watershed response. For sandy soils (K_s= 3.27E-5m/s), all the water does infiltrate into the ground, however the subsurface flow drains slowly and most of the water is retained in the soil matrix.

The model was calibrated for Goodwin Creek watershed using the short rainfall event of October 17, 1981, and verified using the long rainfall event of

December 2, 1983. The simulated hydrograph followed the observed hydrograph trend in both the short duration rainfall event (3.15 hrs), and also the long duration rainfall event (30 hrs).

The conditions of rainfall intensity and soil type for which subsurface flow is important may be inferred from Figure 5.2. For sandy soils at a saturated hydraulic conductivity range of 1.0E-5m/s to 1.0E-3m/s, and the rainfall intensity less than 1in/hr(7.055E-06m/s), the response of a watershed is primarily influenced by subsurface flow. For silty-loam soils at a saturated hydraulic conductivity of 1.0E-6m/s and rainfall intensity around 0.1in/hr(7.055E-07m/s), the response of a watershed is influenced by both surface and the subsurface flow. For clayey soils at a saturated hydraulic conductivity of 1.0E-8m/s and a rainfall intensity exceeding 0.1in/hr(7.055E-07m/s), the watershed response is governed by surface flow.

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Appendix A

SOURCE CODE DOCUMENTATION

```
DEBUG
C  ***********************************************************************
C
C   PROGRAM CASCSUB2D -- SUBSURFACE FLOW CONTRIBUTION TO RAINFALL-
RUNOFF
C               DEVELOPED  BY
C                AMIT SHARMA
C                 09/01/97
C
C  **********************************************************************
C
C  THE PROGRAM  COMPUTES, BOTH SURFACE AND SUBSURFACE FLOW
C
C
====================================================================================
C
C  REAL     HOUT,QOUT,RINDEX,DH,VOUT,DCH,TIMMAX,VSUR
   REAL     HOUT,QOUT,RINDEX,DH,VOUT,DCH,VSUR
   REAL     VSUB,AREAOUT,RETAIN,DUMMY
   REAL     ECONV,INDEXCHAN
   DIMENSION  qmeas1(100,100),qmeas2(100,100)
   DIMENSION  vino(100,100)
   INTEGER  IC,L, icnt
   INTEGER  ISHP(100,100),IMAN(100,100),ISOIL(100,100)
   INTEGER  IPOR(100,100)
   CHARACTER*10  lbl
   CHARACTER dname*20,rname*20,hsubname*20,
  +headline(6)*80,vinfname*20,hchname*20

   DIMENSION  E(100,100),H(100,100),HSUB(100,100),RINT(100,100),
  +          VINF(100,100),CON(100,100),
  +         DQOV(100,100),DQCH(100,100),DQSUB(100,100),
  +         HCH(100,100),XRG(20),YRG(20),RRG(20),PMAN(10),
  +       PINF(10,9),ICHN(29,16,2),CHP(29,3),IQ(20,2),Q(20)
  +        ,PPOR(10)
C
C  ---------------------------------------------------------
C  GENERAL VARIABLE DESCRIPTION
C  ---------------------------------------------------------
C  HOUT = Height of discharged water at the outlet.
C  QOUT = Discharge at the outlet
C  RINDEX = Rainfall index; 1 for rainfall; 0 for no rainfall.
```

```
C   DH  = Change in the height of water (delta H)
C   VOUT = Volume of water at the outlet.
C   DCH = Depth of the channel
C   VSUR  = Volume of water at the surface.
C   ---------------
C   AREAOUT =  Area at the outlet
C   VSUB    =  Volume of water in the subsurface.
C   ---------------
C   ISHP  = (M*N) matrix, determines the shape of the watershed.
C         (1 if the grid cell is within the watershed and 0 if the grid
C         cell is outside of the watershed)
C   IMAN  = (M*N) integer matrix, carrying Manning n code for each grid.
C   ISOIL = (M*N) matrix carrying soil code for each grid cell.
C   ---------------
C   E   = Topographical elevation (M*N)matrix stored in ELAVG.DAT
C   H   = Height of surface water,or overland flow depth.
C   RINT = Rainfall intensity.
C   VINF = Height of infiltrated water, or infiltrated depth.
C   HSUB = Height of subsurface water, or the subsurface depth.
C   POR  = Porosity.
C   CON  = Conductivity.
C   ---------------
C   DQOV = Overland discharge
C   DQCH = Channel discharge.
C   HCH  = Height of water in the channel.
C   XRG  = x cordinate of raingage location,or Column position of each
C        rainfall gage
C   YRG  = y cordinate of raingage location, or Row position of each
C        rainfall gage
C   RRG  = ((NITRN/NREAD)*NRG)matrix that defines rainfall intensities
C        recorded by the raingages.It is read from datafile RAIN.DAT
C   PMAN = A vector of size NMAN,contaning Manning roughness coef.
C        corrosponding to each roughness group.It is read from DATA1 file
C   PINF = (NSOIL*3)matrix contaning infiltration parameters.
C        Hyfraulic Conductivity, Capillary Suction Head,and Soil
C        moisture deficit.
C   ICHN = 3D(NCHN*MAXCHN*2)matrix containing channel element addresses.
C        NCHN =   Total number of channel being considered.
C        MAXCHN = maximum length of any single channel.
C        2 = for row and column numbers.
C   CHP  = (NCHN*3)matrix containing channel parameters.
C        Channel width,Depth, and Manning's roughness coeff.
C   DQSUB= Subflow discharge.
C
C   -------------------------------------------------------
C   OPENING FILES
C   -------------------------------------------------------
      OPEN(UNIT=25,FILE='data1', STATUS ='OLD')
      OPEN(UNIT=27,FILE='out.prn')
      OPEN(UNIT=38,FILE='sub.prn')
      OPEN(29,FILE='rainga.dat',STATUS = 'OLD')
```

```
      OPEN(30,FILE='bug')
      OPEN(37,FILE='plot.out')
      OPEN(60,FILE='cell.data',STATUS = 'OLD')
      OPEN(61,FILE='flow.out')
      OPEN(62,FILE='hch.out')
C     ------------------------------------------------------------
C
C     READS HEADER FILE FOR OUTPUT GRIDS TO  BE READ INTO GRASS
C
      open(unit=44,file='head',status='unknown')
      do 1500 i=1,6
      read(44,1501) headline(i)
 1501 format(a80)
 1500 continue
      close(44)

c     initialize a dummy variable, used to determine the maximum Q
c
      qstop = 0.
      icnt = 0
c
      WRITE(27,180)
      WRITE(38,181)
C
C     ----------------------------------------------------------
C     INPUT-VARIABLE DESCRIPTION
C     ----------------------------------------------------------
C     M = Total number of rows
C     N = Total number of columns
C     W = Grid size (m), or Grid cell resolution.
C     NMAN = Number of surface roughness groups or overland Manning n
C     SDEP = Overland detention storage (m)
C     -----------
C     DT = simulation time step (sec)
C     NITER = Total number of time intervals for the runoff simulation.
C     NITRN = Total number of time intervals for the rainfall duration.
C     NPRN  = Number of time steps to write the output.
C     NPLT  = Number of time steps to update graphics display.
C     ------------
C     JOUT  = Outlet row number
C     KOUT  = Outlet column number
C     SOUT  = Bed Slope for the channel at the outlet.
C     QMAX  = Max. discharge at the outlet to be used for graphics(CMS)
C     WCHOUT= Channel width at the outlet (m)
C     DCHOUT= Channel depth at the outlet (m)
C     RMANOUT=Manning channel roughness coefficient at outlet
C     ------------
C     INDEXINF = Infiltration index:1 for infiltration:0 for no infiltration.
C     NSOIL    = Number of soils with different infiltration parameters.
C     ------------
C     NCHN = Total number of channels.
```

```
C   MAXCHN = Maximum allowable number of channel elements plus one for any
C         channel.
C   ------------
C   IRAIN = rainfall index:1 for raingage data :0 for uniform rainfall.
C   ------------
C   NRG   = total number of rainfall recording raingages.
C   NREAD = ratio between raingage rainfall data time-step and DT.
C   ------------
C   CRAIN = Uniform rainfall intensity (m/s). (IRAIN=0).
C   ------------------------------------------------------------

    READ(25,*) M,N,W,NMAN,SDEP,NPOR
    READ(25,*) DT,NITER,NITRN,NPRN,NPLT,ECONV,INDEXCHAN
    READ(25,*) JOUT,KOUT,SOUT,qmax,WCHOUT,DCHOUT,RMANOUT
    READ(25,*) INDEXINF,NSOIL
    READ(25,*) NCHN,MAXCHN
    READ(25,*) IRAIN
C
C   IF THE RAINFALL SWITCH IS 0.0 THEN UNIFORM VALUE OF RAINFALL
C   IS READ.
C
    IF(IRAIN.EQ.0) READ(25,*) CRAIN
    if(irain.eq.1) read(25,'(a)') lbl
C
C   FOLLOWING READS THE POROSITY VALUES FROM THE INPUT.DATA FILE
C   DEPENDING UPON THE NUMBER OF NPOR VALUES ALSO FROM INPUT.DATA
C
    READ(25,*) (PPOR(J),J=1,NPOR)
C   FOLLOWING READS THE MANNING'S N VALUES FROM THE DATA1 FILE
C   DEPENDING UPON THE NUMBER OF NMAN VALUES ALSO FROM DATA1
C
    READ(25,*) (PMAN(J),J=1,NMAN)

C   FOLLOWING READS THE INFILTRATION PARAMETERS FROM THE DATA1 FILE
C
    IF(INDEXINF.EQ.1) READ(25,*) ((PINF(J,K),K=1,3),J=1,NSOIL)

    IF(IRAIN.EQ.1) READ(29,*) NRG,NREAD
    IF(IRAIN.EQ.1) READ(29,*) (XRG(L),YRG(L),L=1,NRG)
C

    close(25)
    close(29)

C   ---------------------------------------------------
C   OPENING INPUT FILES
C   ---------------------------------------------------
    OPEN(UNIT=21,FILE='shap.dat')
    OPEN(UNIT=22,FILE='elavg.dat')
    OPEN(UNIT=24,FILE='soil.dat')
    OPEN(UNIT=26,FILE='chn.dat')
```

```
      OPEN(UNIT=39,FILE='por.dat')
C     ----------------------------------------------------------
C
C     FOLLOWING READS THE WIDTH,DEPTH AND THE MANNING'S N IN THE
C     CHANNEL
C
      IF(NCHN.NE.0) READ(26,*) ((CHP(L,K),K=1,3),L=1,NCHN)
C     IF(NCHN.NE.0) READ(26,128) (((ICHN(L,J,K),J=1,MAXCHN),
C    +                      K=1,2),L=1,NCHN)
C
C     FOLLOWING READS THE CHANNLE CELL LOCATIONS IN CHN.DAT
C
      IF(NCHN.NE.0) READ(26,*) (((ICHN(L,J,K),J=1,MAXCHN),
     +                      K=1,2),L=1,NCHN)

C     FOLLOWING HELPS IN FINDING OUT THE DISCHARGE IN THE CHANNEL
C     CELLS, IF ONE WANTS TO.
C
      READ(60,*)INDEXFLOW, NCELL
      IF (INDEXFLOW.EQ.1) READ(60,*)((IQ(J,K),K=1,2),J=1,NCELL)
      CLOSE(60)
C
C     FOLLOWING WRITES THE FIRST LINE IN THE FLOW.OUT FILE
C
      WRITE(61,229) ((IQ(J,K),K=1,2),J=1,NCELL)
C     WRITE(62,230) ((HCH(J,K),K=1,2),J=1,NCELL)

C     ----------------------------------------------------------
C     READING SHAP MATIX AND READING ELEVATIONS AND INITIALIZATIONS
C     ----------------------------------------------------------
      DO 150 J=1,M
        DO 151 K=1,N
          IF(NPOR.EQ.1) THEN
            IPOR(J,K)=1
          ELSE
            READ(39,*) IPOR(J,K)
          ENDIF
          READ(21,*) ISHP(J,K)
          READ(22,*) E(J,K)
          E(J,K)=E(J,K)/ECONV
          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)
```

```
OPEN(UNIT=28,FILE='iman.dat')
```

```
      ENDIF
C     ***********************************************
C     THE FOLLOWING 3 LINES MAKE THE "K" OF GREEN-AMPT
C     EQUAL TO THE "K" OF SUBFLOW SUBROUTNE
C     *************************************************
C      HYDRAULIC CONDUCTIVITY HERE IS IN m/s
      IINF=ISOIL(J,K)
      HYDCON=PINF(IINF,1)
      CON(J,K) = HYDCON
C     -----------------------------------------------
C
      H(J,K)=0.
      HCH(J,K)=0.
         VINO(J,K)=0.
      DQOV(J,K)=0.
      DQCH(J,K)=0.
      VINF(J,K)=0.
      HSUB(J,K)=0.
         DQSUB(J,K)=0.
         qmeas1(J,K)=0.
         qmeas2(J,K)=0.
 151 CONTINUE
 150 CONTINUE
   close(21)
   close(22)
   close(24)
   close(26)
   close(28)

C   ------------------------------------------------------
C   MATRIX INITIALIZATION FOR THE LOCATION OF THE CHANNEL NODES
C   ------------------------------------------------------
   DO 160 IC=1,NCHN,1
     DO 175 L=1,MAXCHN,1
C
C   IC is the Link number and L is the Node number.
C
      J=ICHN(IC,L,1)
      K=ICHN(IC,L,2)
C
C   J is the row location and K is the column location.
C
      IF(J.LE.0) GO TO 160
         IF (INDEXCHAN .EQ. 1.0)THEN
      ISHP(J,K)=2
      ENDIF
C
C   When ISHP is equal to 2, then the program designates that grid
C   cell as a channel cell.
C
 175   CONTINUE
```

```
 160 CONTINUE
    open(unit=31,file='bug2')
    open(unit=32,file='bugrain')
    open(unit=33,file='buginf')
    open(unit=34,file='bugover')
    open(unit=35,file='bugsub')
    open(unit=36,file='bugchn')
    open(unit=40,file='hover')
    open(unit=41,file='quatro')
    open(unit=42,file='subonly')
C   ---------------------------------------------
C   ---------------------------------------------
    VIN=0.
    VOUT=0.
    VSUB=0.
    VINFTOT=0.
    RINDEX=1.
    check2=0.
    IFCOUNT=1
    ICOUNT=1
    IPCOUNT=1
    AMAXDEPTH=9E-30
    AMINDEPTH=9E30
    AMAXCDEPTH=9E-30
    AMINCDEPTH=9E30
    AMAXVINF=9E-30
    AMINVINF=9E30
    AMAXRAIN=9E-30
    AMINRAIN=9E30
    AMAXHSUB=9E-30
    AMINHSUB=9E30


    OPEN(UNIT=23,FILE='rain1.dat')
C
C   ----------------------------------------
C   TIME LOOP
C   ----------------------------------------
    DO 10 I=1,NITER
      ICALL=0
          VSUR=0.
          VCHN=0.
          VOVR=0.
          VAR3=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,*) (RRG(L),L=1,NRG)
        ENDIF
      ENDIF
```

```
        close(30)

C      --------------------------------------------------------
C      UPDATE OVERLAND + SUB DEPTH
C      --------------------------------------------------------
      DO 1 J=1,M
        DO 1 K=1,N
C         write(27,*) J, K, HCH(J,K), HCH(2,3)
          IF(ISHP(J,K).EQ.0) GO TO 1
          IF(IRAIN.EQ.0) THEN
C
C      APPLICATION OF UNIFORM RAINFALL INTENSITY
C
            RINT(J,K)=CRAIN
          ELSE
C
C      APPLICATION OF SPATIALLY DISTRIBUTED RAINFALL
C
            IF(ICALL.EQ.1) CALL RAIN(J,K,NRG,XRG,YRG,RRG,RINT)
          ENDIF
          IF(I.GT.NITRN) RINT(J,K)=0.
C
C      DETERMINATION OF MINIMUM AND MAXMIMUM RAINFALL
C      LINES BELOW ARE ONLY FOR GRAPHIC REPRESENTATION
C
      IF (RINT(J,K) .LT. AMINRAIN) AMINRAIN=RINT(J,K)
      IF (RINT(J,K) .GT. AMAXRAIN) AMAXRAIN=RINT(J,K)

C           CALCULATION OF OVERLAND DEPTH BASED ON THE OVERLAND
DISCHARGE
C      FROM THE OVERLAND SUBROUTINE
C
          HOV=DQOV(J,K)*DT/(W*W)
C
C      THE DQOV(J,K) ABOVE IS THE TOTAL DISCHARGE IN THE CELL
C      AFTER CONSEDERING ALL THE 4 CELLS SURROUNDING THE CENTER
C      CELL. HENCE 5 CELLS ARE BEING CONCEDERED FOR TOTAL DQOV
C
C
C      CALCULATION OF THE TOTAL OVERLAND DEPTH
C
          HOV=HOV+H(J,K)+RINDEX*RINT(J,K)*DT
          IF(HOV.LT.0) then
C          HOV=0.
              write(*,*)
              write(*,'(a)') 'Overland depth is negative'
              write(*,*)
                 write(*,*) 'hov =',hov
          GO TO 170
          endif
C
```

```
C       CLCULATION OF SUBSURFACE DEPTH
            HBULK=DQSUB(J,K)*DT/(W*W)
C         HGRD=HBULK/POR(J,K)
            HGRD=HBULK/PPOR(IPOR(J,K))
C
C      IF INDEXINF=1 THEN INFILTRATION OCCURS,OTHERWISE NO
C
         IF(INDEXINF.EQ.1)
   +      CALL INFILT(J,K,DT,ISOIL,VINF,PINF,HOV)
         H(J,K)=HOV
C
         IF(HSUB(J,K).LT.0) then
C         HSUB(J,K)=.00001
             write(*,*)
             write(*,'(a)') 'HSUB IS NEGATIVE'
             write(*,*)
                 write(*,*) 'HSUB(J,K) =',HSUB(J,K)
                 write(*,*) 'DQSUB=',DQSUB(J,K), '  HGRD=',HGRD
         GO TO 170
         endif
C  Save previous HSUB value for printing if it goes negative
            HSUBO=HSUB(J,K)
         HSUB(J,K)=HSUB(J,K)+HGRD+VINF(J,K)-VINO(J,K)
            VINO(J,K)=VINF(J,K)
   IF (H(J,K) .LT. AMINDEPTH) AMINDEPTH=H(J,K)
   IF (H(J,K) .GT. AMAXDEPTH) AMAXDEPTH=H(J,K)
   IF (VINF(J,K) .LT. AMINVINF) AMINVINF=VINF(J,K)
   IF (VINF(J,K) .GT. AMAXVINF) AMAXVINF=VINF(J,K)

         DQOV(J,K)=0.
            DQSUB(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) THEN
                VSUR=VSUR+H(J,K)*W*W
         ENDIF
         IF(ISHP(J,K).EQ.1)VOVR=VOVR+H(J,K)*W*W
            IF(I.EQ.NITER.AND.ISHP(J,K).EQ.1)VSUB=VSUB+HSUB(J,K)*W*W
         IF(I.EQ.NITER.AND.ISHP(J,K).EQ.1)VAR3=VAR3+HSUB(J,K)*W*W
 1    CONTINUE
c     this part of the program is for debugging
c
        do 15 ij = 1, m
           if(i.eq.niter) write(40,*) (ishp(ij,ik),ik=1,n)
 15    continue

c     debug part of the program ends here
c

C
     IF(INDEXCHAN .EQ. 1.0)THEN
```

```
      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)
C          write(36,*)'DQCH(J,K)=',DQCH(J,K)
          DHCH=DQCH(J,K)*DT/(W*WCH)
          HCH(J,K)=HCH(J,K)+DHCH
C
C          ADDING VOLUME OF EXTRA WATER IN THE OVERLAND CELL
C          INTO CHANNEL
C
          IF(H(J,K).GT.SDEP) THEN
            HCH(J,K)=HCH(J,K)+(H(J,K)-SDEP)*W/WCH
            H(J,K)=SDEP
          ENDIF
C
C       ADDING VOLUME OF EXTRA WATER FROM THE SUBSURFACE TO
C       THE CHANNLE
C
            HCH(J,K)=HCH(J,K)+HSUB(J,K)*(W/WCH)
                  check2=check2+HSUB(J,K)
C            write(6,*) HCH(J,K),HSUB(J,K)
                IF(ISHP(J,K) .EQ. 2 )THEN
            HSUB(J,K)=0.
                  ENDIF
C -------------------RESET INFILTRATION FOR CHANNEL
C
          HTOP=DCH+H(J,K)
C
             IF(HCH(J,K).GT.HTOP) THEN
            DH=(HCH(J,K)-HTOP)*WCH/W
            H(J,K)=H(J,K)+DH
            HCH(J,K)=HTOP+DH
          ENDIF
C   FOLLOWING LINES DETERMINE MINIMUM AND THE MAXIMUM
C   DEPTH OF WATER IN THE CHANNEL
C
    IF (HCH(J,K) .LT. AMINCDEPTH) AMINCDEPTH=HCH(J,K)
    IF (HCH(J,K) .GT. AMAXCDEPTH) AMAXCDEPTH=HCH(J,K)
C
C          write(*,*) j,k,hch(j,k),h(j,k),dh
          IF(HCH(J,K).LT.0) then
C          HCH(J,K)=0.
               write(*,*)
               write(*,'(a)') 'Channel depth is negative'
               write(*,*)
```

```
           write(*,*) 'DQCH(4,7) ', DQCH(4,7)
           write(*,*) 'DQCH(5,8) ', DQCH(5,8)
           write(*,*) 'DHCH, DQCH ', DHCH, DQCH(J,K)
               write(*,*) j,k,hch(j,k)
           GO TO 176
          ELSE
          endif
          DQCH(J,K)=0.
C          -------------------------------------------------
C          To see what is going only in the channel.
C
          IF(I .EQ. NITER .AND. ISHP(J,K).EQ.2) THEN
           VSUR=VSUR+HCH(J,K)*W*WCH+H(J,K)*W*W
          ENDIF
C          ------------------------------------------------
          IF(ISHP(J,K).EQ.2)VCHN=VCHN+HCH(J,K)*W*WCH
          IF(I.EQ.NITER.AND.ISHP(J,K).EQ.2)VOVR=VOVR+H(J,K)*W*W
C          IF(I.EQ.NITER) write(40,*) h(j,k),j,k
  3      CONTINUE
  2     CONTINUE
       ENDIF
C      -------------------------------------------------------
C      OVERLAND AND SUBSURFACE FLOW ROUTING
C      --------------------------------------------------------
C
 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
           KK=K-L
C          ---------------------------------------------
           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)
     CALL SUBFLO(W,J,K,JJ,KK,E,HSUB,DQSUB,IPOR,PPOR,CON,DT,I,ISHP,M,N)
      IF (HSUB(J,K).LT.AMINHSUB) AMINHSUB=HSUB(J,K)
      IF (HSUB(J,K).GT.AMAXHSUB) AMAXHSUB=HSUB(J,K)
 40        CONTINUE
 30       CONTINUE
 20     CONTINUE
C      ------------------------------------------------
C      UPDATE CHANNEL DEPTH
C      ------------------------------------------------
C      Print starting subsurface depths for debug
C      write (35,*) "Subsurface depths prior to channel depth calcs"
C        do 183 ik = 1,m
C        write (35, ' (7E10.3)' ) (hsub(ik,il), il=1,n)
C183    continue
C      ---------------------------------------
C      CHANNEL FLOW ROUTING
C      ---------------------------------------
```

```
      IF(INDEXCHAN .EQ. 1.0)THEN
      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)
C
C       JJJ SIGNIFIES THAT THE END OF THE CHANNEL LINK
C        HAS BEEN REACHED.
C
                IF(L .EQ. MAXCHN-1) THEN
                  JJJ = -1
           ELSE
            JJJ=ICHN(IC,L+2,1)
                ENDIF
          IF(JJ.LE.0) GO TO 50
C
C    CALLING CHANNEL SUBROUTINE
C
          CALL CHNCHN(NCHN,W,WCH,DCH,RMANCH,NITER,
   +J,K,JJ,KK,JJJ,E,HCH,ICHN,CHP,DQCH,DT,NCELL,IQ,Q)

 60       CONTINUE
 50     CONTINUE
          ENDIF
C       ---------------------------------------------
C       OUTFLOW DISCHARGE
C       ---------------------------------------------
        HOUT=H(JOUT,KOUT)
          ALFA=SQRT(SOUT)/PMAN(IMAN(JOUT,KOUT))
        QOUTOV=0.
          QOUTCH=0.
        IF(HOUT.GT.SDEP) QOUTOV=W*ALFA*((HOUT-SDEP)**1.667)
        H(JOUT,KOUT)=HOUT-QOUTOV*DT/(W*W)
C
        IF(INDEXCHAN .EQ. 1.0)THEN
        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)
        ENDIF
        QOUT=QOUTOV+QOUTCH
       write(6,5000) i,real(i)*dt/60.0,qout*3.28**3.0
5000     format(1x,'Iteration = ',i7,'  Time (Min) = ',f8.4,
```

```
     &' Outflow (CFS) = ',f15.4)
C
C       TO ASSESS THE TOTAL OUTFLOW VOLUME
C
        VOUT=VOUT+QOUT*DT
           VSUR=VSUR-QOUT*DT
           VCHN=VCHN-QOUTCH*DT
           VOVR=VOVR-QOUTOV*DT
C       -------------------------------------------------------
        if(i.eq.1) qold = 0.0
        IF(((I-1)/NPLT)*NPLT.EQ.I-1) qold = qout
C
C     Determining the Time to Peak and the Peak Flow at the Outlet
C
      if(I.eq.1) then
      qpeak=0.
      tpeak=0.
      endif
      if(qout.gt.qpeak) then
      qpeak=qout
      tpeak=real(i)*dt/60.
      endif
C
C       -------------------------------------------------------
c----->>>     UNIT CHANGE FROM m3/s TO cfs
C     IF((I/NPRN)*NPRN.EQ.I) WRITE(27,190) I*DT/60.,QOUT*(3.28)**3
C     IF((I/NPRN)*NPRN.EQ.I)
C     IF(ICOUNT.EQ.NPRN.OR.ICOUNT.EQ.I) THEN
      IF(ICOUNT.EQ.NPRN.OR.I.EQ.1) THEN
      WRITE(27,190) I*DT/60.,QOUT*(3.28)**3
C
C     WRITES QOUT NOT AT EVERY INCREMENT OF DT, BUT DEPENDING UPON
C     NPRN(SPECIFIED IN DATA1 FILE) AND AND ICOUNT IN FILE OUT.PRN
C
      WRITE(38,'(2x,f7.2,e10.3)') I*DT/60.,QSUB*(3.28)**3
      WRITE(61,112) I*DT/60.,
     +(Q(ILL)*(3.28)**3,ILL=1,NCELL)
C     WRITE(62,113) I*DT/60.,
C    +(HCH(J,K)*(3.28)**3,ILL=1,NCELL)
C
C     WRITES DISCHARGE (Q(ILL))IN FLOW.OUT
C
      IF (I .EQ. 1) ICOUNT=ICOUNT+1
      IF (I .NE. 1) ICOUNT=1
      ELSE
      ICOUNT=ICOUNT+1
      ENDIF
C
       if (i .le. niter) then
       retain=0.
          check1=0.
```

```
          SUM = 0.
       do 75 ik = 1,m
            do 70 il = 1, n
              retain = retain + hsub(ik,il)
              check1 = check1 + hsub(ik,il)
              do 69 im = -1,0,1
              jj=ik+im+1
              kk=il-im
              slope= abs((e(ik,il)-e(jj,kk))/w)
          qmeas2(ik,il)=qmeas2(ik,il)+w*sqrt(slope)*
   @                hsub(ik,il)*con(ik,il)
          qmeas1(ik,il)=qmeas1(ik,il)+w*sqrt(slope)*h(ik,il)
   @                /pman(iman(ik,il))
 69        continue
 70        continue
 75      continue
C
       endif
C
C   WRITING OUTPUT GRIDS
C
     IF (IPCOUNT .EQ. NPLT .OR. I .EQ. 1) THEN
     print*,'Writing Output Grids, IFCOUNT = ',IFCOUNT
     OPEN(UNIT=48,FILE='JUNK',STATUS='UNKNOWN')
     IF (IFCOUNT .LE. 9) THEN
     WRITE(48,1701) IFCOUNT
     WRITE(48,1702) IFCOUNT
     WRITE(48,1703) IFCOUNT
     WRITE(48,1704) IFCOUNT
     WRITE(48,1706) IFCOUNT
 1701 FORMAT('depth.',i1)
 1702 FORMAT('hsub.',i1)
 1703 FORMAT('rain.',i1)
 1704 FORMAT('hch.',i1)
 1706 FORMAT('vinf.',i1)
     else
     endif
     IF (IFCOUNT .GT. 9 .AND.IFCOUNT .LE. 99) THEN
     WRITE(48,1001) IFCOUNT
     WRITE(48,1002) IFCOUNT
     WRITE(48,1003) IFCOUNT
     WRITE(48,1004) IFCOUNT
     WRITE(48,1007) IFCOUNT
 1001 FORMAT('depth.',i2)
 1002 FORMAT('hsub.',i2)
 1003 FORMAT('rain.',i2)
 1004 FORMAT('hch.',i2)
 1007 FORMAT('vinf.',i2)
     else
     endif
     if (IFCOUNT .gt. 99 .and. IFCOUNT .le. 999) then
```

```
      WRITE(48,1601) IFCOUNT
      WRITE(48,1602) IFCOUNT
      WRITE(48,1603) IFCOUNT
      WRITE(48,1604) IFCOUNT
      WRITE(48,1606) IFCOUNT
 1601 FORMAT('depth.',i3)
 1602 FORMAT('hsub.',i3)
 1603 FORMAT('rain.',i3)
 1604 FORMAT('hch.',i3)
 1606 FORMAT('vinf.',i3)
      else
      endif
      rewind(48)
      read(48,1006) dname
      read(48,1006) hsubname
      read(48,1006) rname
      read(48,1006) hchname
      read(48,1006) vinfname
 1006 format(a20)
      close(48)
C
C   Writing the Output Grids (Depth,Subsurface depth, Rain,
C   Channel depth, and Infiltration )
C
      open(unit=50,file=dname,status='unknown')
      open(unit=51,file=hsubname,status='unknown')
      open(unit=52,file=rname,status='unknown')
      open(unit=53,file=hchname,status='unknown')
      open(unit=54,file=vinfname,status='unknown')
      do 1010 j1=1,6
      write(50,1020) headline(j1)
      write(51,1020) headline(j1)
      write(52,1020) headline(j1)
      write(53,1020) headline(j1)
      write(54,1020) headline(j1)
 1020 format(a80)
 1010 continue
      DUMMY= 0.
      do 1030 j1=1,M
      do 1040 k1=1,N
      if(ISHP(j1,k1).eq.2)then
        write(50,*) DUMMY
        write(53,*) HCH(j1,k1)*1E3
      endif
        if(ISHP(j1,k1).eq.1)then
          write(53,*) DUMMY
          write(50,*) H(j1,k1)*1E6
      endif
C********************************
C******** Test of problem with hch.1 not having enough data
C******** Write out value of ISHP if it is less than 1 to hch file
```

```
C******** Above code will write out to file for ISHP = 1 and ISHP = 2 only
C    if(ISHP(j1,k1).lt.1) then
C      write(53,*) 'ISHP = ', ISHP(j1,k1), ' at cell ', j1, k1
C    endif
C******** End of Test Code
C*******************************
      if(ISHP(j1,k1).eq.0.)then
        write(53,*) DUMMY
        write(50,*) DUMMY
    endif

    write(51,*) HSUB(j1,k1)*1E3
c
c    Note : The rainfall intensity is being written in
c    Inches/Hour * 1000
c
    write(52,*) RINT(j1,k1)*1E3*3600/.0254
    write(54,*) VINF(j1,k1)*1E3
 1040 continue
 1030 continue
    close(50)
    close(51)
    close(52)
    close(53)
    close(54)
    IFCOUNT=IFCOUNT+1
    IF (I .EQ. 1) IPCOUNT=IPCOUNT+1
    IF (I .NE. 1) IPCOUNT=1
    ELSE
    IPCOUNT=IPCOUNT+1
    ENDIF
C
      write(41,'(f7.2,5e10.3)')i*dt/60.,VOVR*3.28**3,VCHN*3.28**3,
   @  vin*3.28**3,vout*3.28**3,retain*W*W*3.28**3

C      write(35,*) 'Iteration = ',i
CB      write(35,*) 'H=(OVERLAND WATER DEPTH MATRIX)'
CB      do 80 ik = 1, m
CB        write(35,'(7e10.3)') (h(ik,il),il=1,n)
C80B    continue
CB        write(35,*) 'HCH=(CHANNEL WATER DEPTH MATRIX)'
CB      do 81 ik = 1, m
CB        write(35,'(7e10.3)') (hch(ik,il),il=1,n)
C81B    continue
C        write(35,*) 'DISCHARGE MATRIX FOR THE SURFACE'
c      do 82 ik = 1, m
C        write(35,'(7e10.3)') (qmeas1(ik,il),il=1,n)
c82     continue
C        write(35,*) 'HSUB=SUBSURFACE WATER DEPTH MATRIX'
C      do 83 ik = 1, m
C        write(35,'(7e10.3)') (hsub(ik,il),il=1,n)
```

```
C83     continue
CB        write(35,*) 'VINF=DEPTH OF INFILTRATED WATER MATRIX'
CB      do 84 ik = 1, m
CB        write(35,'(7e10.3)') (vinf(ik,il),il=1,n)
C84B    continue
C         write(35,*) 'DQCH=DISCHARGE IN THE CHNL MATRIX'
C       do 85 ik = 1, m
C         write(35,'(7e10.3)') (dqch(ik,il),il=1,n)
C85     continue
C       write(35,*) 'DISCHARGE MATRIX FOR THE SUBSURFACE'
C       do 86 ik = 1, m
C         write(35,'(7e10.3)') (qmeas2(ik,il),il=1,n)
C86     continue
C       write(35,*) 'DISCHARGE MATRIX FOR THE SUBSURFACE'
C       do 87 ik = 1, m
C         write(35,'(7e10.3)') (dqsub(ik,il).il=1.n)
C87     continue

CB        write(35,'(a,f10.4)')'Retained portion of hsub in soil='.retain
CB        write(35.'(2(a,f9.4,2x))')'totalsub='.check1.'dumpsub='.check2
c       write(35,'(a,e10.3)')'QSUB =',
c   @   w*alpha*hsub(jout-1,kout)*3.28**3.
c       write(35,'(2x,e10.3.2i3)') hsub(jout-1.kout).jout-1.kout
C       write(35,*)

C       if (qstop .le. qout*(3.28)**3) then
C         qstop = qout*(3.28)**3
C       elseif (qstop .gt. qout*(3.28)**3) then
C         icnt = icnt + 1
C       endif
C       if (icnt .gt. 4) goto 169
C       write(27,'(a,/,2f15.6)')
C   @ 'Height of Overland and Sub'. hov,hsoil
 10  CONTINUE
       retain = retain*W*W*3.28**3.
          check1 = check1*W*W*3.28**3.
          check2 = check2*W*W*3.28**3.
     SUM = RETAIN + VSUR*(3.28**3) + VOUT*(3.28**3)
C    print *,SUM,RETAIN,VSUR*(3.28**3),VOUT*(3.28**3)
C
C    -------------------------------------------------------
C    END OF TIME LOOP
C    -------------------------------------------------------
C
     close(23)
C    -------------------------------------------------------
C---->>>    UNIT CHANGE FROM m3 TO ft3
 169 WRITE(27,200) VIN*(3.28**3),VINFTOT*(3.28**3),RETAIN
    +        ,CHECK2
     WRITE(27,210) VSUR*(3.28**3),VOVR*(3.28**3),VCHN*(3.28**3),
    @VOUT*(3.28**3)
```

```
      WRITE(27,'(//,a,f15.6,/,a,f15.6)')
      GO TO 179
 170  WRITE(27,220) J,K,I*DT,DQOV(J,K)
      WRITE(38,220) J,K,I*DT,HGRD
 176  WRITE(27,220) J,K,I*DT,HCH(J,K)

 179  CONTINUE
C     ------------------------------------------------------------
C
C     FORMAT STATEMENTS
C
 180  FORMAT(//' TIME(MIN)  DISCHARGE(CFS)'/)
 181  FORMAT(//' TIME(MIN)  DISCHARGE(CFS)'/)

 190  FORMAT(2X,F15.2,F14.5)
 200  FORMAT(//'VOLUME IN (FT)3=        ',25X,F25.6/
     +'VOLUME INFILTRATED (FT^3)=       ',16X,F25.6/
     +'VOLUME OF WATER RETAINED IN THE SUBSOIL (FT^3) =  ',
     +F25.6/
     +'SUBFLOW CONTRIBUTION TO SURFACE VOLUME (FT^3) =  ',
     +1X,F25.6)
 229  FORMAT('DISCHARGE AT: ',20(2I3,'    '))
 112  FORMAT(2X,F7.2,20F10.3)
 210  FORMAT(//'SURFACE VOLUME (FT^3) =  ',
     +23X,F25.6/,
     +'OVERLAND CONTRIBUTION TO SURFACE VOLUME (FT^3)=  ',
     +3X,F25.6/,
     +'CHANNEL CONTRIBUTION TO SURFACE VOLUME (FT^3) =  ',
     +1X,F25.6/,
     +'VOLUME OUT (FT^3) =  ',
     +31X,F25.6)
 220  FORMAT(/'PROGRAM STOPPED FOR NEGATIVE DEPTH',2I4,3F15.6)
      WRITE(27,221)SUM
 221  FORMAT('SUM (FT^3)= ',37X,F25.6)
      WRITE(27,222)qpeak*(3.28**3),tpeak
 222  FORMAT(//'PEAK DISCHARGE IN CFS=',F15.6/'TIME TO PEAK IN MIN=',
     +   F15.6/)
C     ------------------------------------------------------------
      close(31)
      close(32)
      close(33)
      close(34)
      close(35)
      close(40)
      close(36)
      close(61)
      close(62)
C
C     Writing Min. and Max. values for plotting purposes
C
      write(37,*) ' '
```

```
      write(37,*) 'Minimum and Maximum values for the plotting purposes'
      write(37,*) ' '
      write(37,*) 'Min. Overland Depth (m x 1E3)     =',
     &AMINDEPTH*1E3
      write(37,*) 'Max. Overland Depth (m x 1E3)     =',
     &AMAXDEPTH*1E3
      write(37,*) 'Min. Channel Depth (m x 1E53      =',
     &AMINCDEPTH*1E3
      write(37,*) 'Max. Channel Depth (m x 1E3)      =',
     &AMAXCDEPTH*1E3
      write(37,*) 'Min. Subsurface Depth (m x 1E3)     =',
     &AMINHSUB*1E3
      write(37,*) 'Max. Subsurface Depth (m x 1E3)     =',
     &AMAXHSUB*1E3
      write(37,*) 'Min. VINF (m x 1E3)           =',
     &AMINVINF*1E3
      write(37,*) 'Max. VINF (m x 1E3)           =',
     &AMAXVINF*1E3
      write(37,*) 'Min. RINT (in/hr x 1E3)    =',
     &AMINRAIN*1E3*3600/.0254
      write(37,*) 'Max. RINT (in/hr x 1E3)    =',
     &AMAXRAIN*1E3*3600/.0254
      STOP
      END
C
C   ======================================
      SUBROUTINE RAIN(J,K,NRG,XRG,YRG,RRG,RINT)
C   ======================================
      DIMENSION XRG(NRG),YRG(NRG),RINT(100,100),RRG(NRG)
      REAL     TOTDIST, TOTRAIN
      INTEGER  L,J,K
C
      RINT(J,K)=0.
      TOTDIST=0.
      TOTRAIN=0.
C
      DO 1 L=1,NRG
        XJ=FLOAT(J)
        XK=FLOAT(K)
        DIST=SQRT((XJ-YRG(L))**2+(XK-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 in/hr TO m/s
 2    RINT(J,K)=RINT(J,K)*0.0254/3600.
      RETURN
```

```
      END
C
C     ==========================================
      SUBROUTINE INFILT(J,K,DT,ISOIL,VINF,PINF,HOV)
C     ==========================================
      INTEGER   ISOIL(100,100)
      INTEGER   IINF
      DIMENSION  VINF(100,100),PINF(1,3)
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)
      P2=HYDCON*(VINF(J,K)+CS*SMD)
C      write(33,*)'CS= ',CS,'SMD= ',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     =================================================
      DIMENSION  E(100,100),H(100,100),DQOV(100,100),PMAN(10)
      INTEGER   IMAN(100,100)
      REAL      A,S0,HH,ALFA,SF,DQQ,DHDX,RMAN
      DATA      A/1./
C
      S0=(E(J,K)-E(JJ,KK))/W
C      write(34,*)'SO= ',s0
      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    ==========================================================
      SUBROUTINE SUBFLO(W,J,K,JJ,KK,E,HSUB,DQSUB,IPOR,PPOR,CON,DT,I
     +,ISHP,M,N)
C    ==========================================================
      DIMENSION  E(100,100),HSUB(100,100),DQSUB(100,100),
     +PPOR(10),CON(100,100),ISHP(100,100)
      DATA     A/1./
          INTEGER IPOR(100,100)
          REAL RPOR
      S0=(E(J,K)-E(JJ,KK))/W
C     write(42,*)'SO= ',s0,'E(J,K)= ',E(J,K),'J= ',J,'K=',K
      SF=S0
      IF(ABS(SF).LT.1E-20) SF=1E-20
      HH=HSUB(J,K)
      RPOR=PPOR(IPOR(J,K))
      IF(SF.LT.0) HH=HSUB(JJ,KK)
      IF(SF.LT.0) RPOR=PPOR(IPOR(JJ,KK))
      ALFA=(ABS(SF))*CON(J,K)
      DQQ=SIGN(A,SF)*W*ALFA*HH/RPOR
C    ------------------
C    This set of code checks the value of DQQ and limits DQQ and DQSUB(J,K)
C    to assure that the volume of water removed from a cell (DQQ*DT) is
C    less than or equal to (HSUB(J,K)/POR(J,K)*W*W), which is the original
C    volume of water in the cell.
C    ------------------
C    First check the sign of DT to find which way the flow is going.
C    If DQQ is > 0, the flow is going down the channel (from J,K to JJ,KK).
      IF (DQQ .GT. 0) THEN
C       Check to see if DQQ needs to be limited to the cell volume, or
C       if it must also account for previous transfers (DQSUB(J,K)
        IF (DQSUB(J,K) .LT. 0 ) THEN
        IF ((DQQ-DQSUB(J,K))*DT .GT. (HSUB(J,K)/RPOR*W*W)) THEN
          DQQ = (HSUB(J,K)/RPOR*W*W)/DT + DQSUB(J,K)
        ENDIF
        ELSE
      IF (DQQ*DT .GT. (HSUB(J,K)/RPOR*W*W))  THEN
         DQQ = (HSUB(J,K)/RPOR*W*W)/DT
        ENDIF
        ENDIF

C    Now handle the case where the flow is going up the channel (from JJ,KK)
      ELSE
        IF (DQSUB(JJ,KK) .LT. 0 ) THEN
        IF ((-DQQ-DQSUB(JJ,KK))*DT .GT. (HSUB(JJ,KK)/RPOR*W*W))THEN
          DQQ = -(HSUB(J,K)/RPOR*W*W)/DT + DQSUB(J,K)
         ENDIF
         ENDIF
        IF (ABS(DQQ)*DT .GT. (HSUB(JJ,KK)/RPOR*W*W)) THEN
```

```
         DQQ= -(HSUB(JJ,KK)/RPOR*W*W)/DT

        ENDIF

      ENDIF
C
      DQSUB(J,K)=DQSUB(J,K)-DQQ
      DQSUB(JJ.KK)=DQSUB(JJ,KK)+DQQ
C
      RETURN
      END
C

C     ==============================================================
      SUBROUTINE CHNCHN(NCHN,W,WCH.DCH,RMANCH,NITER.
     +J.K.JJ,KK.JJJ.E,HCH,ICHN,CHP.DQCH.DT.NCELL,IQ.Q)

C     ==============================================================
      DIMENSION E(100,100),HCH(100,100),ICHN(29,16,2),CHP(29,3).
     +         DQCH(100,100),IQ(20,2),Q(20)
      REAL      A,S0,HH,DQ,AREA,SF,WP,DHDX
      INTEGER   IIC
      DATA      A/1./
C
      S0=(E(J,K)-DCH-E(JJ,KK)+DCH)/W
C      write(36,*)'J, K = ', J, K
C      DHDX=(HCH(JJ,KK)-HCH(J,K))/W
C      SF=S0-DHDX+1E-30
C      IF(ABS(SF).LT.1E-20) SF=1E-20
C      HH=HCH(J,K)
C      IF(SF.LT.0) THEN
        IF(JJJ.LT.0) THEN
          DO 5 IIC=1,NCHN,1
            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
                   IJUN=IIC
                   GO TO 7
                   ENDIF
 5         CONTINUE
        ENDIF
 7             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 .AND. JJJ .LT. 0)THEN
              WCH=CHP(IJUN,1)
              DCH=CHP(IJUN,2)
              RMANCH=CHP(IJUN,3)
              HH=HCH(JJ,KK)
            ENDIF
      WP=WCH+2.*HH
```

```
C     IF(HH.GT.HCH(J,K)) WP=WCH+2.*HCH(J,K)
      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)
C     ------------------
C     This set of code checks the value of DQ and limits DQ and DQCH(J,K)
C     to assure that the volume of water removed from a cell (DQ*DT) is
C     less than or equal to (HCH(J,K)*W*WCH), which is the original
C     volume of water in the cell.
C     ------------------
C     First check the sign of DT to find which way the flow is going.
C     If DQ is > 0, the flow is going down the channel (from J,K to JJ,KK).
      IF (DQ .GT. 0) THEN
C     write(36,*)'DQ= ',dq,' DQCH(J,K)=',dqch(J,K), J, K,HCH(J,K)
C       Check to see if DQ needs to be limited to the cell volume, or
C       if it must also account for previous transfers (DQCH(J,K)
        IF (DQCH(J,K) .LT. 0 ) THEN
        IF ((DQ-DQCH(J,K))*DT .GT. (HCH(J,K)*W*WCH)) THEN
          DQ = (HCH(J,K)*W*WCH)/DT + DQCH(J,K)
        ENDIF
        ELSE
      IF (DQ*DT .GT. (HCH(J,K)*W*WCH))  THEN
         DQ = (HCH(J,K)*W*WCH)/DT
        ENDIF
        ENDIF

C     Now handle the case where the flow is going up the channel (from JJ,KK)
      ELSE
        IF (DQCH(JJ,KK) .LT. 0 ) THEN
        IF ((-DQ-DQCH(JJ,KK))*DT .GT. (HCH(JJ,KK)*W*WCH)) THEN
          DQ = -(HCH(J,K)*W*WCH)/DT + DQCH(J,K)
         ENDIF
         ENDIF
        IF (ABS(DQ)*DT .GT. (HCH(JJ,KK)*W*WCH)) THEN
          DQ= -(HCH(JJ,KK)*W*WCH)/DT

        ENDIF

      ENDIF
      DQCH(J,K)=DQCH(J,K)-DQ
      DQCH(JJ,KK)=DQCH(JJ,KK)+DQ
      RETURN
      END
```

Appendix B

Graph.f ---- SOURCE CODE FOR GRAPHIC VISULIZATION

```
C   This Program creates 9 different windows and  plots raster maps
C   of various physical processes in GRASS environment.
C
      character name*5,name1*6,name2*5,name3*5,name4*4
      name='rain.'
      name1='depth.'
      name2='vinf.'
      name3='hsub.'
      name4='hch.'
      open(unit=9,file='graph.sh',status='unknown')
      print*,'Input Minimum and Maximum maps to plot'
      read(5,*) amin,amax
      min=int(amin)
      max=int(amax)
      write(9,600)
      write(9,610)
      write(9,620)
      write(9,630)
      write(9,640)
      write(9,650)
      write(9,652)
      write(9,653)
      write(9,651)
  600 format(1x,'d.frame -c frame=rainfall at=33,66,0,33')
  610 format(1x,'d.frame -c frame=depth at=33,66,66,99')
  620 format(1x,'d.frame -c frame=vinf at=33,66,33,66')
  630 format(1x,'d.frame -c frame=hsub at=0,33,0,33')
  640 format(1x,'d.frame -c frame=hch at=0,33,33,66')
  650 format(1x,'d.frame -c frame=title at=0,33,66,99')
  651 format(1x,'d.frame -c frame=elev at=66,99,66,99')
  652 format(1x,'d.frame -c frame=iman at=66,99,0,33')
  653 format(1x,'d.frame -c frame=soil at=66,99,33,66')
  500 format(1x,'d.frame -s frame=rainfall')
  510 format(1x,'d.frame -s frame=depth')
  520 format(1x,'d.frame -s frame=vinf')
  530 format(1x,'d.frame -s frame=hsub')
```

```
  540 format(1x,'d.frame -s frame=hch')
  550 format(1x,'d.frame -s frame=title')
  551 format(1x,'d.frame -s frame=elev')
  552 format(1x,'d.frame -s frame=iman')
  553 format(1x,'d.frame -s frame=soil')
  560 format(1x,'d.rast elev')
  561 format(1x,'d.rast iman')
  562 format(1x,'d.rast soil')
  563 format(1x,'d.mapgraph input=elev_map')
  564 format(1x,'d.mapgraph input=iman_map')
  565 format(1x,'d.mapgraph input=soil_map')
  566 format(1x,'d.mapgraph input=title_map')
  700 format(1x,'d.mapgraph input=rain_map')
  710 format(1x,'d.mapgraph input=depth_map')
  720 format(1x,'d.mapgraph input=vinf_map')
  730 format(1x,'d.mapgraph input=hsub_map')
  740 format(1x,'d.mapgraph input=hch_map')
  940 format(1x,'d.rast shap')
      write(9,700)
      write(9,710)
      write(9,720)
      write(9,730)
      write(9,740)
  800 format(1x,'d.mapgraph input=time.',i1)
  810 format(1x,'d.mapgraph input=time.',i2)
  820 format(1x,'d.mapgraph input=time.',i3)
      write(9,552)
      write(9,561)
      write(9,564)
      write(9,553)
      write(9,562)
      write(9,565)
      write(9,551)
      write(9,560)
      write(9,563)
      write(9,550)
      write(9,566)
      do 10 i=min,max
c  26 format(1x,'d.vect goodws color=black')
      if (i .le. 9) then
      write(9,500)
      write(9,20) name,i
c     write(9,26)
      write(9,30) name,i
      write(9,700)
      write(9,800) i
```

```
   20 format(1x,'d.rast ',a5,i1)
   30 format(1x,'echo ',a5,i1)
      write(9,510)
      write(9,232) name1,i
c      write(9,26)
      write(9,234) name1,i
      write(9,710)
      write(9,800) i
  232 format(1x,'d.rast ',a6,i1)
  234 format(1x,'echo ',a6,i1)
      write(9,520)
      write(9,20) name2,i
c      write(9,26)
      write(9,30) name2,i
      write(9,720)
      write(9,800) i
      write(9,530)
      write(9,236) name3,i
c      write(9,26)
      write(9,238) name3,i
      write(9,730)
      write(9,800) i
  236 format(1x,'d.rast ',a5,i1)
  238 format(1x,'echo ',a5,i1)
      write(9,540)
      write(9,940)
      write(9,240) name4,i
c      write(9,26)
      write(9,242) name4,i
      write(9,740)
      write(9,800) i
  240 format(1x,'d.rast -o ',a4,i1)
  242 format(1x,'echo ',a4,i1)
      else
      endif
      if (i .gt. 9 .and. i .le. 99) then
      write(9,500)
      write(9,40) name,i
c      write(9,26)
      write(9,50) name,i
      write(9,700)
      write(9,810) i
   40 format(1x,'d.rast ',a5,i2)
   50 format(1x,'echo ',a5,i2)
      write(9,510)
      write(9,332) name1,i
```

```
c    write(9,26)
     write(9,334) name1,i
     write(9,710)
     write(9,810) i
 332 format(1x,'d.rast ',a6,i2)
 334 format(1x,'echo ',a6,i2)
     write(9,520)
     write(9,40) name2,i
c    write(9,26)
     write(9,50) name2,i
     write(9,720)
     write(9,810) i
     write(9,530)
     write(9,336) name3,i
c    write(9,26)
     write(9,338) name3,i
     write(9,730)
     write(9,810) i
 336 format(1x,'d.rast ',a5,i2)
 338 format(1x,'echo ',a5,i2)
     write(9,540)
     write(9,940)
     write(9,340) name4,i
c    write(9,26)
     write(9,342) name4,i
     write(9,740)
     write(9,810) i
 340 format(1x,'d.rast -o ',a4,i2)
 342 format(1x,'echo ',a4,i2)
     else
     endif
     if (i .gt. 99 .and. i.le. 999) then
     write(9,500)
     write(9,60) name,i
c    write(9,26)
     write(9,70) name,i
     write(9,700)
     write(9,820) i
  60 format(1x,'d.rast ',a5,i3)
  70 format(1x,'echo ',a5,i3)
     write(9,510)
     write(9,432) name1,i
c    write(9,26)
     write(9,434) name1,i
     write(9,710)
     write(9,820) i
```

```
 432 format(1x,'d.rast ',a6,i3)
 434 format(1x,'echo ',a6,i3)
     write(9,520)
     write(9,60) name2,i
c     write(9,26)
     write(9,70) name2,i
     write(9,720)
     write(9,820) i
     write(9,530)
     write(9,436) name3,i
c     write(9,26)
     write(9,438) name3,i
     write(9,730)
     write(9,820) i
 436 format(1x,'d.rast ',a5,i3)
 438 format(1x,'echo ',a5,i3)
     write(9,540)
     write(9,940)
     write(9,440) name4,i
c     write(9,26)
     write(9,442) name4,i
     write(9,740)
     write(9,820) i
 440 format(1x,'d.rast -o ',a4,i3)
 442 format(1x,'echo ',a4,i3)
     else
     endif
  10 continue
     stop
     end
```

Appendix C

Data1 — INPUT DATA FILE FOR GOODWIN CREEK WATERSHED

```
47   75   126.83     3    0.018       3
05.  5760   2532       12    576   10.0  1.0
44   3   0.01      1500.0   23.63  6.05  0.037
1    3
19    16
1
1.E-5
0.437
0.453
0.471
0.08
0.08
0.08
3.56E-7  0.0800  0.08
2.86E-6  0.1600  0.08
2.76E-5  0.1600  0.08
```

Rainga.dat ---- RAIN GUAGE SPECIFICATION FOR GOODWIN CREEK WATERSHED

```
17   12
4.5  43.5
15.5  26.5
33.5  20.5
45.5  16.5
41.5  9.5
44.5  25.5
58.5  11.5
57.5  16.5
62.5  14.5
19.5  26.5
28.5  26.5
33.5  23.5
22.5  34.5
30.5  33.5
37.5  29.5
39.5  18.5
52.5  19.5
```

CHN.DAT — CHANNEL DATA SPECIFICATION FOR GOODWIN CREEK WATERSHED

```
 28.99  4.00  0.037
 32.71  4.20  0.037
 23.45  4.34  0.037
 18.35  4.34  0.037
 15.24  4.50  0.037
 17.70  4.70  0.037
 37.97  4.97  0.037
 28.24  5.32  0.037
 23.63  6.05  0.037
 12.88  3.87  0.037
 22.42  3.98  0.037
 14.48  4.11  0.037
 15.70  3.40  0.037
 16.32  3.55  0.037
 13.65  3.83  0.037
 8.58   4.30  0.037
 7.42   4.50  0.037
 6.00   3.00  0.037
 7.00   3.50  0.037

13 13 13 13 13 13 12 12 12 11 11 11 11 11 11 -1
69 68 67 66 65 64 64 63 62 62 61 60 59 58 57 -1

11 11 12 12 12 12 12 13 14 14 15 15 16 16 16 -1
57 56 56 55 54 53 52 52 52 51 51 50 50 49 48 -1

16 16 16 16 16 15 15 15 14 14 14 14 14 -1  0  0
48 47 46 45 44 44 43 42 42 41 40 39 38 -1  0  0

14 15 15 15 16 16 17 18 19 19 20 20 21 -1  0  0
38 38 37 36 36 35 35 35 35 34 34 33 33 -1  0  0

21 21 22 22 23 23 24 24 25 25 25 25 -1  0  0  0
33 32 32 31 31 30 30 29 29 28 27 26 -1  0  0  0

25 25 25 25 25 25 25 25 26 26 -1  0  0  0  0  0
```

```
26 25 24 23 22 21 20 19 19 18 -1  0  0  0  0  0

26 26 27 27 27 28 29 30 30 31 31 32 -1  0  0  0
18 17 17 16 15 15 15 15 14 14 13 13 -1  0  0  0

32 32 33 34 34 35 36 36 37 37 38 39 39 40 41 -1
13 12 12 12 11 11 11 10 10  9  9  9  8  8  8 -1

41 41 42 43 43 44 44 44 44  0  0  0  0  0  0  0
 8  7  7  7  6  6  5  4  3  0  0  0  0  0  0  0

 8  8  9  9  9  9  9  9  9  9 10 -1  0  0  0  0
49 48 48 47 46 45 44 43 42 41 41 -1  0  0  0  0

10 11 11 12 12 13 13 14 -1  0  0  0  0  0  0  0
41 41 40 40 39 39 38 38 -1  0  0  0  0  0  0  0

17 17 17 17 18 18 18 18 18 17 17 16 -1  0  0  0
56 55 54 53 53 52 51 50 49 49 48 48 -1  0  0  0

23 23 24 24 25 25 25 25 26 26 27 27 27 27 -1  0
57 56 56 55 55 54 53 52 52 51 51 50 49 48 -1  0

27 28 28 28 27 27 26 26 25 25 24 24 23 23 -1  0
48 48 47 46 46 45 45 44 44 43 43 42 42 41 -1  0

23 23 23 22 22 22 22 22 21 21 21 -1  0  0  0  0
41 40 39 39 38 37 36 35 35 34 33 -1  0  0  0  0

33 33 32 32 32 31 31 30 30 30 29 -1  0  0  0  0
37 36 36 35 34 34 33 33 32 31 31 -1  0  0  0  0

29 28 28 27 27 26 26 26 26 25 -1  0  0  0  0  0
31 31 30 30 29 29 28 27 26 26 -1  0  0  0  0  0

38 37 37 36 35 35 34 34 34 33 33 32 31 31 30 -1
29 29 28 28 28 27 27 26 25 25 24 24 24 23 23 -1

30 30 29 29 28 28 27 27 27 26 -1  0  0  0  0  0
23 22 22 21 21 20 20 19 18 18 -1  0  0  0  0  0
```

Appendix D

FOR CLAY(2): K = 1.0E-11 m/sec
Rainfall duration = 16.67 min
Response computed for 66.67 min

Time step = 2 (**EARLY**)

H= **OVERLAND WATER DEPTH MATRIX** (m)

```
.000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00
.000E+00 .382E-03 .000E+00 .382E-03 .382E-03 .382E-03 .000E+00
.000E+00 .392E-03 .000E+00 .392E-03 .400E-03 .400E-03 .000E+00
.000E+00 .389E-03 .000E+00 .389E-03 .400E-03 .400E-03 .000E+00
.000E+00 .386E-03 .000E+00 .373E-03 .381E-03 .379E-03 .000E+00
.000E+00 .402E-03 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00
.000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00
```

HCH= **CHANNEL WATER DEPTH MATRIX**(m)

```
.000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00
.000E+00 .000E+00 .381E-03 .000E+00 .000E+00 .000E+00 .000E+00
.000E+00 .000E+00 .416E-03 .000E+00 .000E+00 .000E+00 .000E+00
.000E+00 .000E+00 .422E-03 .000E+00 .000E+00 .000E+00 .000E+00
.000E+00 .000E+00 .428E-03 .000E+00 .000E+00 .000E+00 .000E+00
.000E+00 .000E+00 .416E-03 .431E-03 .442E-03 .446E-03 .000E+00
.000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00
```

HSUB= **SUBSURFACE WATER DEPTH MATRIX**(m)

```
.000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00
.000E+00 .400E-09 .000E+00 .400E-09 .400E-09 .400E-09 .000E+00
.000E+00 .400E-09 .000E+00 .400E-09 .400E-09 .400E-09 .000E+00
.000E+00 .400E-09 .000E+00 .400E-09 .400E-09 .400E-09 .000E+00
.000E+00 .400E-09 .000E+00 .400E-09 .400E-09 .400E-09 .000E+00
.000E+00 .400E-09 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00
.000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00
```

VINF= **DEPTH OF INFILTRATED WATER MATRIX**(m)

```
.000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00
.000E+00 .400E-09 .400E-09 .400E-09 .400E-09 .400E-09 .000E+00
.000E+00 .400E-09 .400E-09 .400E-09 .400E-09 .400E-09 .000E+00
.000E+00 .400E-09 .400E-09 .400E-09 .400E-09 .400E-09 .000E+00
.000E+00 .400E-09 .400E-09 .400E-09 .400E-09 .400E-09 .000E+00
.000E+00 .400E-09 .400E-09 .400E-09 .400E-09 .400E-09 .000E+00
.000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00
```

Time step = 50 (**PEAK**)

H= **OVERLAND WATER DEPTH MATRIX**(m)

```
.000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00
.000E+00 .843E-03 .000E+00 .844E-03 .854E-03 .855E-03 .000E+00
.000E+00 .103E-02 .000E+00 .104E-02 .129E-02 .129E-02 .000E+00
.000E+00 .107E-02 .000E+00 .109E-02 .163E-02 .165E-02 .000E+00
.000E+00 .104E-02 .000E+00 .859E-03 .126E-02 .123E-02 .000E+00
.000E+00 .154E-02 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00
.000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00
```

HCH= **CHANNEL WATER DEPTH MATRIX(m)**

```
.000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00
.000E+00 .000E+00 .831E-03 .000E+00 .000E+00 .000E+00 .000E+00
.000E+00 .000E+00 .165E-02 .000E+00 .000E+00 .000E+00 .000E+00
.000E+00 .000E+00 .240E-02 .000E+00 .000E+00 .000E+00 .000E+00
.000E+00 .000E+00 .302E-02 .000E+00 .000E+00 .000E+00 .000E+00
.000E+00 .000E+00 .366E-02 .413E-02 .605E-02 .222E-01 .000E+00
.000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00
```

HSUB= **SUBSURFACE WATER DEPTH MATRIX**(m)

```
.000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00
.000E+00 .100E-07 .000E+00 .100E-07 .100E-07 .100E-07 .000E+00
.000E+00 .100E-07 .000E+00 .100E-07 .100E-07 .100E-07 .000E+00
.000E+00 .100E-07 .000E+00 .100E-07 .100E-07 .100E-07 .000E+00
.000E+00 .100E-07 .000E+00 .100E-07 .100E-07 .100E-07 .000E+00
.000E+00 .100E-07 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00
.000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00
```

VINF= **DEPTH OF INFILTRATED WATER MATRIX**(m)

```
.000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00
.000E+00 .100E-07 .100E-07 .100E-07 .100E-07 .100E-07 .000E+00
.000E+00 .100E-07 .100E-07 .100E-07 .100E-07 .100E-07 .000E+00
.000E+00 .100E-07 .100E-07 .100E-07 .100E-07 .100E-07 .000E+00
.000E+00 .100E-07 .100E-07 .100E-07 .100E-07 .100E-07 .000E+00
.000E+00 .100E-07 .100E-07 .100E-07 .100E-07 .100E-07 .000E+00
.000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00
```

Time Step = 100 (**AFTER PEAK**)

H= **OVERLAND WATER DEPTH MATRIX**(m)

```
.000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00
.000E+00 .300E-04 .000E+00 .301E-04 .304E-04 .304E-04 .000E+00
.000E+00 .401E-04 .000E+00 .403E-04 .572E-04 .574E-04 .000E+00
.000E+00 .441E-04 .000E+00 .448E-04 .860E-04 .866E-04 .000E+00
.000E+00 .442E-04 .000E+00 .343E-04 .681E-04 .655E-04 .000E+00
.000E+00 .800E-04 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00
.000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00
```

HCH= **CHANNEL WATER DEPTH MATRIX**(m)

```
.000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00
.000E+00 .000E+00 .273E-04 .000E+00 .000E+00 .000E+00 .000E+00
.000E+00 .000E+00 .733E-04 .000E+00 .000E+00 .000E+00 .000E+00
.000E+00 .000E+00 .122E-03 .000E+00 .000E+00 .000E+00 .000E+00
.000E+00 .000E+00 .169E-03 .000E+00 .000E+00 .000E+00 .000E+00
.000E+00 .000E+00 .226E-03 .271E-03 .430E-03 .287E-02 .000E+00
.000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00
```

HSUB= **SUBSURFACE WATER DEPTH MATRIX**(m)

```
.000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00
.000E+00 .200E-07 .000E+00 .200E-07 .200E-07 .200E-07 .000E+00
.000E+00 .200E-07 .000E+00 .200E-07 .200E-07 .200E-07 .000E+00
.000E+00 .200E-07 .000E+00 .200E-07 .200E-07 .200E-07 .000E+00
.000E+00 .200E-07 .000E+00 .200E-07 .200E-07 .200E-07 .000E+00
.000E+00 .200E-07 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00
.000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00
```

VINF= **DEPTH OF INFILTRATED WATER MATRIX**(m)

```
.000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00
.000E+00 .200E-07 .200E-07 .200E-07 .200E-07 .200E-07 .000E+00
.000E+00 .200E-07 .200E-07 .200E-07 .200E-07 .200E-07 .000E+00
.000E+00 .200E-07 .200E-07 .200E-07 .200E-07 .200E-07 .000E+00
.000E+00 .200E-07 .200E-07 .200E-07 .200E-07 .200E-07 .000E+00
.000E+00 .200E-07 .200E-07 .200E-07 .200E-07 .200E-07 .000E+00
.000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00
```

Time Step = 200 (**LATE**)

H= **OVERLAND WATER DEPTH MATRIX**(m)

```
.000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00
.000E+00 .677E-05 .000E+00 .678E-05 .682E-05 .682E-05 .000E+00
.000E+00 .903E-05 .000E+00 .906E-05 .129E-04 .129E-04 .000E+00
.000E+00 .993E-05 .000E+00 .100E-04 .194E-04 .195E-04 .000E+00
.000E+00 .994E-05 .000E+00 .763E-05 .154E-04 .147E-04 .000E+00
.000E+00 .180E-04 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00
.000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00
```

HCH= **CHANNEL WATER DEPTH MATRIX**(m)

```
.000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00
.000E+00 .000E+00 .604E-05 .000E+00 .000E+00 .000E+00 .000E+00
.000E+00 .000E+00 .164E-04 .000E+00 .000E+00 .000E+00 .000E+00
.000E+00 .000E+00 .274E-04 .000E+00 .000E+00 .000E+00 .000E+00
.000E+00 .000E+00 .378E-04 .000E+00 .000E+00 .000E+00 .000E+00
.000E+00 .000E+00 .506E-04 .608E-04 .964E-04 .662E-03 .000E+00
.000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00
```

HSUB= **SUBSURFACE WATER DEPTH MATRIX(m)**

```
.000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00
.000E+00 .400E-07 .000E+00 .400E-07 .400E-07 .400E-07 .000E+00
.000E+00 .400E-07 .000E+00 .400E-07 .400E-07 .400E-07 .000E+00
.000E+00 .400E-07 .000E+00 .400E-07 .400E-07 .400E-07 .000E+00
.000E+00 .400E-07 .000E+00 .400E-07 .400E-07 .400E-07 .000E+00
.000E+00 .400E-07 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00
.000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00
```

VINF= DEPTH OF INFILTRATED WATER MATRIX(m)

```
.000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00
.000E+00 .400E-07 .400E-07 .400E-07 .400E-07 .400E-07 .000E+00
.000E+00 .400E-07 .400E-07 .400E-07 .400E-07 .400E-07 .000E+00
.000E+00 .400E-07 .400E-07 .400E-07 .400E-07 .400E-07 .000E+00
.000E+00 .400E-07 .400E-07 .400E-07 .400E-07 .400E-07 .000E+00
.000E+00 .400E-07 .400E-07 .400E-07 .400E-07 .400E-07 .000E+00
.000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00
```

FOR SAND(2): K= 5.0E-4 m/sec
Rainfall duration = 16.67 min
Response computed for 66.67 min

Time Step = 2 (**EARLY**)

H= **OVERLAND WATER DEPTH MATRIX** (m)

```
.000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00
.000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00
.000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00
.000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00
.000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00
.000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00
.000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00
```

HCH= **CHANNEL WATER DEPTH MATRIX** (m)

```
.000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00
.000E+00 .000E+00 .381E-03 .000E+00 .000E+00 .000E+00 .000E+00
.000E+00 .000E+00 .400E-03 .000E+00 .000E+00 .000E+00 .000E+00
.000E+00 .000E+00 .400E-03 .000E+00 .000E+00 .000E+00 .000E+00
.000E+00 .000E+00 .400E-03 .000E+00 .000E+00 .000E+00 .000E+00
.000E+00 .000E+00 .400E-03 .401E-03 .407E-03 .409E-03 .000E+00
.000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00
```

HSUB= **SUBSURFACE WATER DEPTH MATRIX** (m)

```
.000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00
.000E+00 .400E-03 .000E+00 .400E-03 .400E-03 .400E-03 .000E+00
.000E+00 .400E-03 .000E+00 .400E-03 .400E-03 .400E-03 .000E+00
.000E+00 .400E-03 .000E+00 .400E-03 .400E-03 .400E-03 .000E+00
.000E+00 .400E-03 .000E+00 .399E-03 .399E-03 .399E-03 .000E+00
.000E+00 .400E-03 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00
.000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00
```

VINF= **DEPTH OF INFILTRATED WATER MATRIX** (m)

```
.000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00
.000E+00 .400E-03 .400E-03 .400E-03 .400E-03 .400E-03 .000E+00
.000E+00 .400E-03 .400E-03 .400E-03 .400E-03 .400E-03 .000E+00
.000E+00 .400E-03 .400E-03 .400E-03 .400E-03 .400E-03 .000E+00
.000E+00 .400E-03 .400E-03 .400E-03 .400E-03 .400E-03 .000E+00
.000E+00 .400E-03 .400E-03 .400E-03 .400E-03 .400E-03 .000E+00
.000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00
```

Time Step = 50 (**PEAK**)

H= **OVERLAND WATER DEPTH MATRIX** (m)

```
.000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00
.000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00
.000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00
.000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00
.000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00
.000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00
.000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00
```

HCH= **CHANNEL WATER DEPTH MATRIX** (m)

```
.000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00
.000E+00 .000E+00 .809E-03 .000E+00 .000E+00 .000E+00 .000E+00
.000E+00 .000E+00 .124E-02 .000E+00 .000E+00 .000E+00 .000E+00
.000E+00 .000E+00 .159E-02 .000E+00 .000E+00 .000E+00 .000E+00
.000E+00 .000E+00 .191E-02 .000E+00 .000E+00 .000E+00 .000E+00
.000E+00 .000E+00 .219E-02 .248E-02 .342E-02 .128E-01 .000E+00
.000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00
```

HSUB= **SUBSURFACE WATER DEPTH MATRIX** (m)

```
.000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00
.000E+00 .960E-02 .000E+00 .960E-02 .960E-02 .960E-02 .000E+00
.000E+00 .991E-02 .000E+00 .991E-02 .999E-02 .999E-02 .000E+00
.000E+00 .984E-02 .000E+00 .984E-02 .100E-01 .100E-01 .000E+00
.000E+00 .976E-02 .000E+00 .902E-02 .881E-02 .861E-02 .000E+00
.000E+00 .101E-01 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00
.000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00
```

VINF= **DEPTH OF INFILTRATED WATER MATRIX (m)**

```
.000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00
.000E+00 .100E-01 .100E-01 .100E-01 .100E-01 .100E-01 .000E+00
.000E+00 .100E-01 .100E-01 .100E-01 .100E-01 .100E-01 .000E+00
.000E+00 .100E-01 .100E-01 .100E-01 .100E-01 .100E-01 .000E+00
.000E+00 .100E-01 .100E-01 .100E-01 .100E-01 .100E-01 .000E+00
.000E+00 .100E-01 .100E-01 .100E-01 .100E-01 .100E-01 .000E+00
.000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00
```

Time Step = 100 (**AFTER PEAK**)

H= **OVERLAND WATER DEPTH MATRIX** (m)

```
.000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00
.000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00
.000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00
.000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00
.000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00
.000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00
.000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00
```

HCH= **CHANNEL WATER DEPTH MATRIX** (m)

```
.000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00
.000E+00 .000E+00 .266E-04 .000E+00 .000E+00 .000E+00 .000E+00
.000E+00 .000E+00 .116E-03 .000E+00 .000E+00 .000E+00 .000E+00
.000E+00 .000E+00 .212E-03 .000E+00 .000E+00 .000E+00 .000E+00
.000E+00 .000E+00 .305E-03 .000E+00 .000E+00 .000E+00 .000E+00
.000E+00 .000E+00 .370E-03 .513E-03 .823E-03 .395E-02 .000E+00
.000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00
```

HSUB= **SUBSURFACE WATER DEPTH MATRIX** (m)

```
.000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00
.000E+00 .882E-02 .000E+00 .882E-02 .882E-02 .882E-02 .000E+00
.000E+00 .969E-02 .000E+00 .969E-02 .993E-02 .993E-02 .000E+00
.000E+00 .952E-02 .000E+00 .952E-02 .100E-01 .100E-01 .000E+00
.000E+00 .929E-02 .000E+00 .735E-02 .688E-02 .642E-02 .000E+00
.000E+00 .102E-01 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00
.000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00
```

VINF= **DEPTH OF INFILTRATED WATER MATRIX** (m)

```
.000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00
.000E+00 .100E-01 .100E-01 .100E-01 .100E-01 .100E-01 .000E+00
.000E+00 .100E-01 .100E-01 .100E-01 .100E-01 .100E-01 .000E+00
.000E+00 .100E-01 .100E-01 .100E-01 .100E-01 .100E-01 .000E+00
.000E+00 .100E-01 .100E-01 .100E-01 .100E-01 .100E-01 .000E+00
.000E+00 .100E-01 .100E-01 .100E-01 .100E-01 .100E-01 .000E+00
.000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00
```

Time Step = 200 (**LATE**)

H= **OVERLAND WATER DEPTH MATRIX** (m)

```
.000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00
.000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00
.000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00
.000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00
.000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00
.000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00
.000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00
```

HCH= **CHANNEL WATER DEPTH MATRIX** (m)

```
.000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00
.000E+00 .000E+00 .595E-05 .000E+00 .000E+00 .000E+00 .000E+00
.000E+00 .000E+00 .102E-03 .000E+00 .000E+00 .000E+00 .000E+00
.000E+00 .000E+00 .194E-03 .000E+00 .000E+00 .000E+00 .000E+00
.000E+00 .000E+00 .272E-03 .000E+00 .000E+00 .000E+00 .000E+00
.000E+00 .000E+00 .337E-03 .443E-03 .684E-03 .304E-02 .000E+00
.000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00
```

HSUB= **SUBSURFACE WATER DEPTH MATRIX** (m)

```
.000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00
.000E+00 .744E-02 .000E+00 .744E-02 .744E-02 .744E-02 .000E+00
.000E+00 .915E-02 .000E+00 .915E-02 .964E-02 .964E-02 .000E+00
.000E+00 .893E-02 .000E+00 .893E-02 .997E-02 .997E-02 .000E+00
.000E+00 .845E-02 .000E+00 .515E-02 .458E-02 .400E-02 .000E+00
.000E+00 .103E-01 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00
.000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00
```

VINF= **DEPTH OF INFILTRATED WATER MATRIX** (m)

```
.000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00
.000E+00 .100E-01 .100E-01 .100E-01 .100E-01 .100E-01 .000E+00
.000E+00 .100E-01 .100E-01 .100E-01 .100E-01 .100E-01 .000E+00
.000E+00 .100E-01 .100E-01 .100E-01 .100E-01 .100E-01 .000E+00
.000E+00 .100E-01 .100E-01 .100E-01 .100E-01 .100E-01 .000E+00
.000E+00 .100E-01 .100E-01 .100E-01 .100E-01 .100E-01 .000E+00
.000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00
```

FOR GRAVEL(2): K= 3.0E-2 m/sec
Rainfall Duration = 16.67 min
Response computed for = 66.67 min

Time Step = 2 (**EARLY**)

H= **OVERLAND WATER DEPTH MATRIX** (m)

```
.000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00
.000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00
.000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00
.000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00
.000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00
.000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00
.000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00
```

HCH= **CHANNEL WATER DEPTH MATRIX** (m)

```
.000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00
.000E+00 .000E+00 .381E-03 .000E+00 .000E+00 .000E+00 .000E+00
.000E+00 .000E+00 .408E-03 .000E+00 .000E+00 .000E+00 .000E+00
.000E+00 .000E+00 .416E-03 .000E+00 .000E+00 .000E+00 .000E+00
.000E+00 .000E+00 .424E-03 .000E+00 .000E+00 .000E+00 .000E+00
.000E+00 .000E+00 .416E-03 .461E-03 .491E-03 .503E-03 .000E+00
.000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00
```

HSUB= **SUBSURFACE WATER DEPTH MATRIX** (m)

```
.000E+00 .000E+00 .000E+00 .000E+0  .000E+0  .000E+0  .000E+0
.000E+00 .380E-03 .000E+00 .380E-03 .380E-03 .380E-03 .000E+0
.000E+00 .396E-03 .000E+00 .396E-03 .400E-03 .400E-03 .000E+0
.000E+00 .392E-03 .000E+00 .392E-03 .400E-03 .400E-03 .000E+0
.000E+00 .388E-03 .000E+00 .347E-03 .335E-03 .323E-03 .000E+0
.000E+00 .404E-03 .000E+0  .000E+0  .000E+0  .000E+0  .000E+0
.000E+00 .000E+00 .000E+0  .000E+0  .000E+0  .000E+0  .000E+0
```

VINF= **DEPTH OF INFILTRATED WATER MATRIX** (m)

```
.000E+00 .000E+0  .000E+0  .000E+0  .000E+0  .000E+00 .000E+0
.000E+00 .400E-03 .400E-03 .400E-03 .400E-03 .400E-03 .000E+0
.000E+00 .400E-03 .400E-03 .400E-03 .400E-03 .400E-03 .000E+0
.000E+00 .400E-03 .400E-03 .400E-03 .400E-03 .400E-03 .000E+0
.000E+00 .400E-03 .400E-03 .400E-03 .400E-03 .400E-03 .000E+0
.000E+00 .400E-03 .400E-03 .400E-03 .400E-03 .400E-03 .000E+0
.000E+00 .000E+0  .000E+0  .000E+0  .000E+00 .000E+00 .000E+0
```

Time Step = 50 (**PEAK**)

H= **OVERLAND WATER DEPTH MATRIX** (m)

```
.000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00
.000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00
.000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00
.000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00
.000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00
.000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00
.000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00
```

HCH= **CHANNEL WATER DEPTH MATRIX** (m)

```
.000E+00 .000E+0  .000E+0  .000E+0  .000E+00 .000E+00 .000E+00
.000E+00 .000E+00 .809E-03 .000E+0  .000E+00 .000E+00 .000E+00
.000E+00 .000E+00 .145E-02 .000E+0  .000E+00 .000E+00 .000E+00
.000E+00 .000E+00 .216E-02 .000E+0  .000E+00 .000E+00 .000E+00
.000E+00 .000E+00 .275E-02 .000E+0  .000E+00 .000E+00 .000E+00
.000E+00 .000E+0  .345E-02 .404E-02 .594E-02 .217E-01 .000E+00
.000E+00 .000E+0  .000E+0  .000E+0  .000E+00 .000E+00 .000E+00
```

HSUB= **SUBSURFACE WATER DEPTH MATRIX** (m)

```
.000E+00 .000E+00 .000E+00 .000E+0  .000E+0  .000E+0  .000E+00
.000E+00 .196E-02 .000E+00 .196E-02 .196E-02 .196E-02 .000E+00
.000E+00 .324E-02 .000E+00 .324E-02 .387E-02 .387E-02 .000E+00
.000E+00 .368E-02 .000E+00 .368E-02 .563E-02 .563E-02 .000E+00
.000E+00 .348E-02 .000E+00 .156E-02 .179E-02 .157E-02 .000E+00
.000E+00 .637E-02 .000E+00 .000E+0  .000E+0  .000E+0  .000E+00
.000E+00 .000E+0  .000E+00 .000E+0  .000E+0  .000E+0  .000E+00
```

VINF= **DEPTH OF INFILTRATED WATER MATRIX** (m)

```
.000E+00 .000E+0  .000E+0  .000E+0  .000E+0  .000E+0  .000E+0
.000E+00 .100E-01 .100E-01 .100E-01 .100E-01 .100E-01 .000E+0
.000E+00 .100E-01 .100E-01 .100E-01 .100E-01 .100E-01 .000E+0
.000E+00 .100E-01 .100E-01 .100E-01 .100E-01 .100E-01 .000E+0
.000E+00 .100E-01 .100E-01 .100E-01 .100E-01 .100E-01 .000E+0
.000E+00 .100E-01 .100E-01 .100E-01 .100E-01 .100E-01 .000E+0
.000E+00 .000E+0  .000E+0  .000E+0  .000E+0  .000E+0  .000E+0
```

Time Step = 100 (**AFTER PEAK**)

H = **OVERLAND WATER DEPTH MATRIX** (m)

```
.000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00
.000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00
.000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00
.000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00
.000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00
.000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00
.000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00
```

HCH= **CHANNEL WATER DEPTH MATRIX** (m)

```
.000E+00 .000E+00 .000E+0  .000E+0  .000E+0  .000E+00 .000E+0
.000E+00 .000E+00 .266E-04 .000E+0  .000E+0  .000E+00 .000E+0
.000E+00 .000E+00 .943E-04 .000E+0  .000E+0  .000E+00 .000E+0
.000E+00 .000E+00 .197E-03 .000E+0  .000E+0  .000E+00 .000E+0
.000E+00 .000E+00 .297E-03 .000E+0  .000E+0  .000E+00 .000E+0
.000E+00 .000E+00 .536E-03 .626E-03 .991E-03 .548E-02 .000E+0
.000E+00 .000E+00 .000E+0  .000E+0  .000E+0  .000E+00 .000E+0
```

HSUB= **SUBSURFACE WATER DEPTH MATRIX** (m)

```
.000E+00 .000E+0  .000E+00 .000E+0  .000E+0  .000E+0  .000E+0
.000E+00 .922E-05 .000E+00 .922E-05 .922E-05 .922E-05 .000E+0
.000E+00 .363E-04 .000E+00 .363E-04 .704E-04 .704E-04 .000E+0
.000E+00 .717E-04 .000E+00 .717E-04 .274E-03 .274E-03 .000E+0
.000E+00 .950E-04 .000E+00 .264E-04 .790E-04 .674E-04 .000E+0
.000E+00 .546E-03 .000E+00 .000E+0  .000E+0  .000E+0  .000E+0
.000E+00 .000E+0  .000E+00 .000E+0  .000E+0  .000E+0  .000E+0
```

VINF= **DEPTH OF INFILTRATED WATER MATRIX** (m)

```
.000E+00 .000E+0  .000E+0  .000E+0  .000E+0  .000E+00 .000E+0
.000E+00 .100E-01 .100E-01 .100E-01 .100E-01 .100E-01 .000E+0
.000E+00 .100E-01 .100E-01 .100E-01 .100E-01 .100E-01 .000E+0
.000E+00 .100E-01 .100E-01 .100E-01 .100E-01 .100E-01 .000E+0
.000E+00 .100E-01 .100E-01 .100E-01 .100E-01 .100E-01 .000E+0
.000E+00 .100E-01 .100E-01 .100E-01 .100E-01 .100E-01 .000E+0
.000E+00 .000E+0  .000E+0  .000E+0  .000E+0  .000E+00 .000E+0
```

Time Step = 200 (**LATE**)

H= **OVERLAND WATER DEPTH MATRIX** (m)

```
.000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+0
.000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+0
.000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+0
.000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+0
.000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+0
.000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+0
.000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+0
```

HCH= **CHANNEL WATER DEPTH MATRIX** (m)

```
.000E+00 .000E+00 .000E+0  .000E+0  .000E+0  .000E+0  .000E+0
.000E+00 .000E+00 .595E-05 .000E+0  .000E+0  .000E+0  .000E+0
.000E+00 .000E+00 .123E-04 .000E+0  .000E+0  .000E+0  .000E+0
.000E+00 .000E+00 .200E-04 .000E+0  .000E+0  .000E+0  .000E+0
.000E+00 .000E+00 .287E-04 .000E+0  .000E+0  .000E+0  .000E+0
.000E+00 .000E+00 .402E-04 .523E-04 .848E-04 .732E-03 .000E+0
.000E+00 .000E+00 .000E+0  .000E+0  .000E+0  .000E+0  .000E+0
```

HSUB= **SUBSURFACE WATER DEPTH MATRIX** (m)

```
.000E+00 .000E+0  .000E+00 .000E+0  .000E+0  .000E+0  .000E+0
.000E+00 .204E-09 .000E+00 .204E-09 .204E-09 .204E-09 .000E+0
.000E+00 .100E-08 .000E+00 .100E-08 .387E-08 .387E-08 .000E+0
.000E+00 .245E-08 .000E+00 .245E-08 .367E-07 .367E-07 .000E+0
.000E+00 .399E-08 .000E+00 .937E-09 .111E-07 .938E-08 .000E+0
.000E+00 .238E-06 .000E+00 .000E+0  .000E+0  .000E+0  .000E+0
.000E+00 .000E+0  .000E+00 .000E+0  .000E+0  .000E+0  .000E+0
```

VINF= **DEPTH OF INFILTRATED WATER MATRIX** (m)

```
.000E+00 .000E+0  .000E+0  .000E+0  .000E+0  .000E+0  .000E+0
.000E+00 .100E-01 .100E-01 .100E-01 .100E-01 .100E-01 .000E+0
.000E+00 .100E-01 .100E-01 .100E-01 .100E-01 .100E-01 .000E+0
.000E+00 .100E-01 .100E-01 .100E-01 .100E-01 .100E-01 .000E+0
.000E+00 .100E-01 .100E-01 .100E-01 .100E-01 .100E-01 .000E+0
.000E+00 .100E-01 .100E-01 .100E-01 .100E-01 .100E-01 .000E+0
.000E+00 .000E+0  .000E+0  .000E+0  .000E+0  .000E+0  .000E+0
```